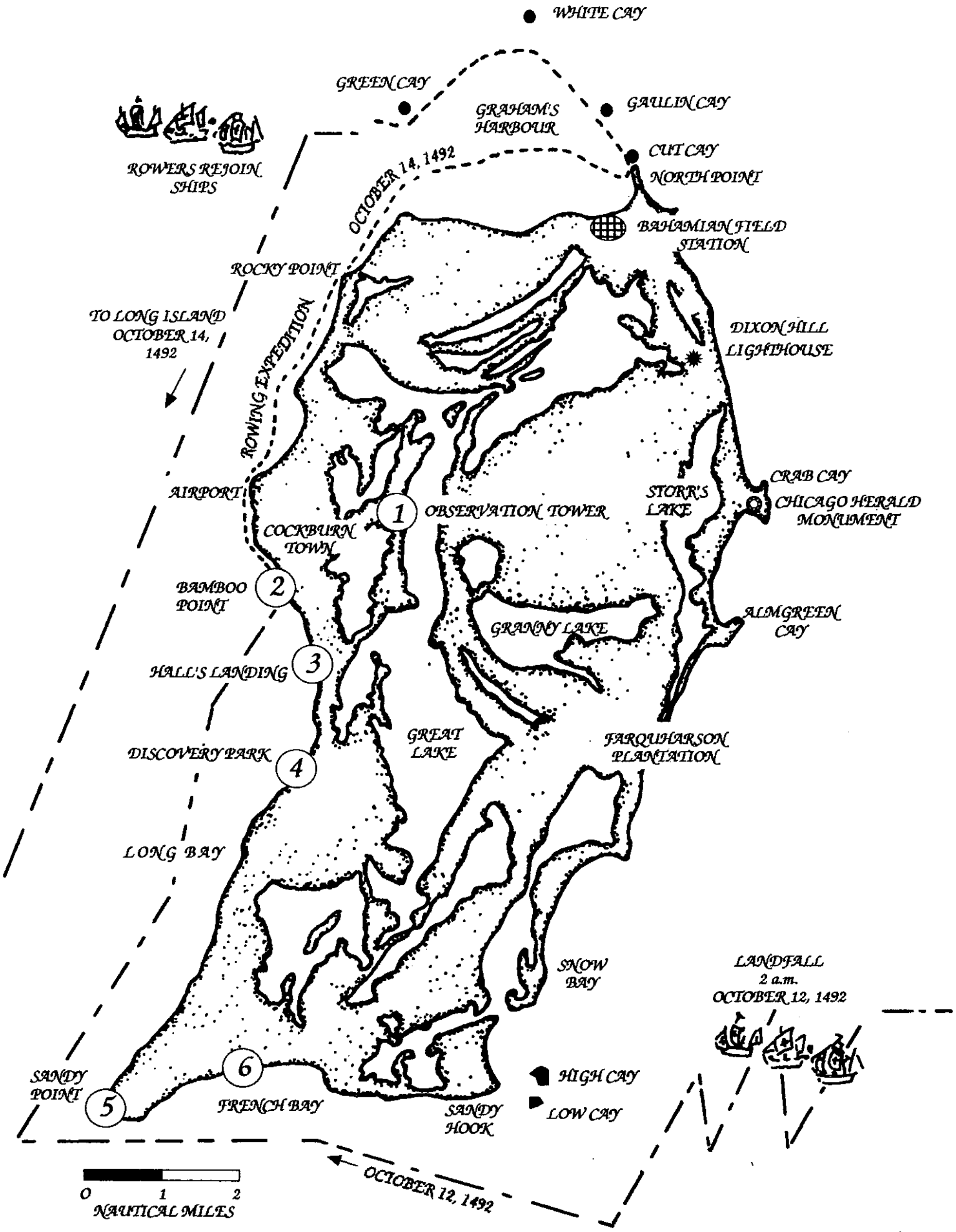
MISCELLANEOUS REPORT NO. 2

THE GEOLOGY OF COLUMBUS' LANDFALL: A FIELD GUIDE TO THE HOLOCENE GEOLOGY OF SAN SALVADOR, BAHAMAS

edited by Mark R. Boardman and Cindy Carney



prepared for the 1992 Annual Meeting of the Geological Society of America

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Cover illustration: Map of San Salvador, Bahamas, showing reconstruction of Columbus' landfall and sailing route around the island.

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We thank the many students who have added to our knowledge by pushing us to explain processes and see things in new perspectives during the annual summer field course taught on San Salvador and Andros Island. Hays Cummins, Arnie Miller, Dave Meyer, and Paul Potter have added significantly to the ideas expressed in this guidebook. In addition, graduate students from Miami University, Wright State University, and the University of Cincinnati have contributed to our understanding of the Bahamas through our involvement in their graduate research activities. Neil Sealey (College of the Bahamas) was instrumental in making possible the trip to Joulters. Don and Kathy Gerace and the staff of the Bahamian Field Station made the many extra efforts to make our work on San Salvador successful. Ben Bohl and the staff of the Forfar Field Station on Andros Island provided the critical logistic support for our work on Joulters. The Bahamian Government provided the several research permits and permitted the movement of scientific gear into and out of the Bahamas, and we are grateful for their cooperation. Bill McIntire worked diligently to meet photographic demands, and we are grateful to the media specialists at both Wright State University and Miami University for their professional services. Funding for the work expressed in this guidebook came from Miami University and Wright State University as well as a grant from the National Science Foundation (EAR 90-04872).

INTRODUCTION

When Columbus landed on San Salvador, he probably saw an island similar to what is there today. However, even in the past 500 years, many geologically significant changes have occurred. If Columbus were to return today, what would he find changed? Would he be able to anchor in the same spot? Would the passages through the reef be the same? Would the Indian villages be located in the same areas?

In fact, there have been changes. Dunes have eroded, beaches and strand plains have prograded and eroded, reefs have flourished and declined, tidal channels have opened and closed, seagrass meadows have expanded and contracted, beachrock has been created and exumed, and storms have done whatever storms do. In short, processes of carbonate accumulation and diagenesis have continued as usual. During this field trip we will focus our attention on aspects of carbonate sedimentology which are examples of relatively rapid change and natural variability.

OVERVIEW OF THE GEOLOGY OF THE BAHAMAS

As we travel to San Salvador, Bahamas, we will cross over many areas which are well-known in the geologic literature. From the air we will view the lateral facies transitions of Bimini islands and lagoon, Great Bahama Bank, Joulters Cays, Tongue of the Ocean, New Providence Island, Schooner Cays ooid shoal, Eleuthera Island, and Cat Island. The expected flight path is shown in figure 1.

THE FLIGHT
(geology from several thousand feet in the air)

Platform topography

As we leave the United States we will fly over the mixed clastic and carbonate barrier islands off Fort Lauderdale and cross the Straits of Florida (a channel 800 m deep and 100 km wide), which separates the United States from the Bahamas. Our first "landfall" in the Bahamas will be the Bimini Islands, on the western margin of Great Bahama Bank. The transition between the Straits of Florida and this Bahama platform is abrupt. On a clear day, the dark blue water of the Straits changes to the lighter blue and green of the shallow (<5 m deep) Great Bahama Bank over a lateral distance of a few hundred meters. This topographic gradient is among the steepest in the world and includes "the wall" (also called the "drop-off"). The abrupt change of depth is an important feature of Bahamian platforms. A second important feature is that the topography of the platform is extraordinarily flat, and water depths are extremely shallow (fig. 2). The relief on the tops of the platforms (<5 m relief over 100 km) is among the lowest in the world (0.003°).

Western margin

Islands, ooid sand shoals, and reefs are located on the east and west margins of the platform and constitute the shallowest (or emerged) portions of the platform. Bimini is an emerged Pleistocene and Holocene beach ridge and sand shoal which today encloses a shallow (< 2 m deep) lagoon (Scoffin, 1970; Strasser and Davaud, 1986). To the south of Bimini, for hundreds of kilometers, are ooid shoals and islands (and a few reefs) which are situated in a narrow (1-2 km wide) zone parallel to the bank margin. Based on the large-scale features of the sand shoals that we can see from

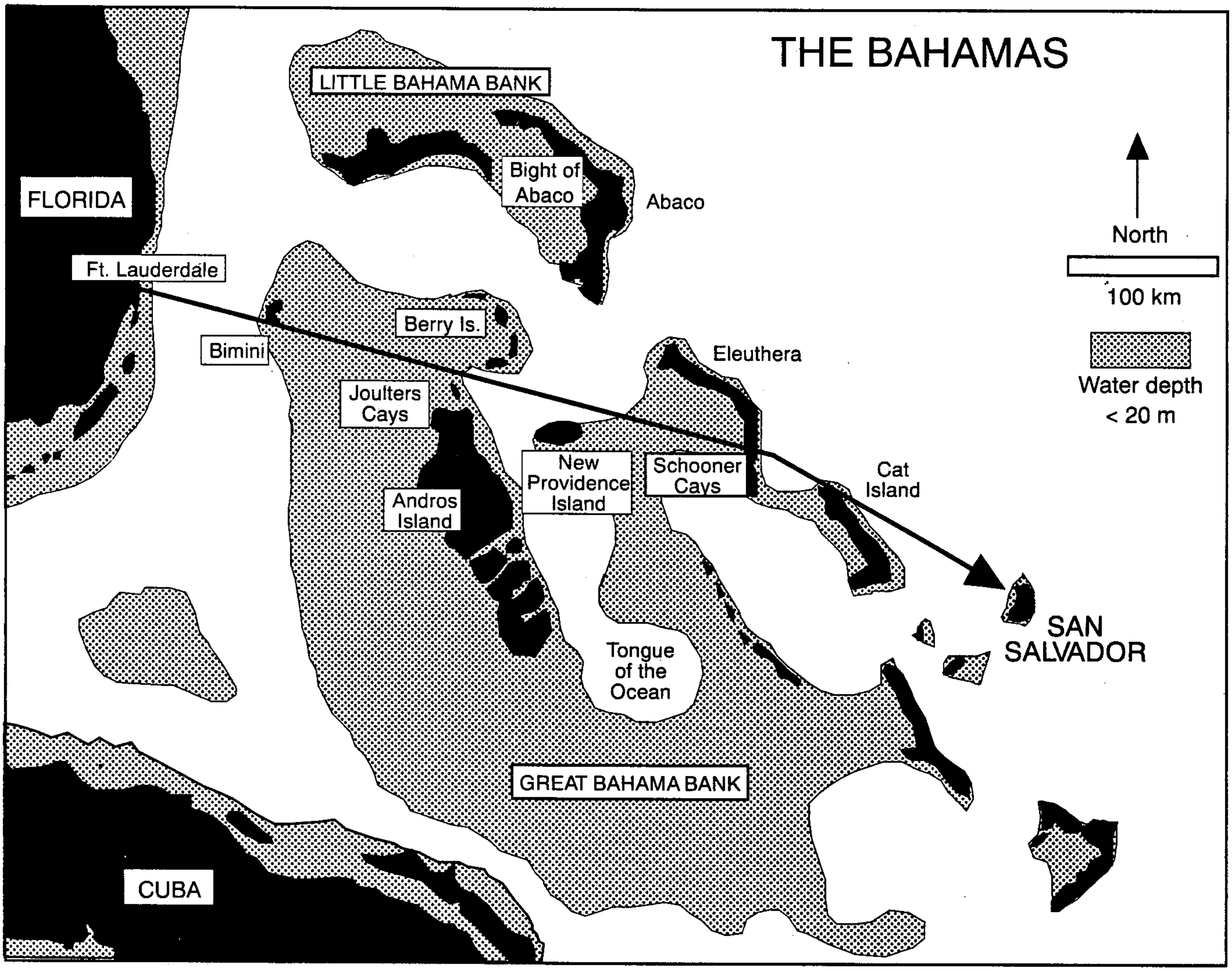


FIGURE 1.—Map of the Bahamas and anticipated flight path.

the air, the dominant movement of sand is flood oriented (lagoonward). However, an enormous amount of offbank movement of sediment is recognized by seismic investigations and sediment coring on the shallow margin and in the deeper, periplatform environments (Hine and others, 1981; Wilbur and others, 1990).

Central lagoon

Both large meadows and smaller patches of seagrass make the shallow bottom in the lagoon appear darker. Sand waves, generated by storms and/or generated before the creation of the barrier rim (*i.e.*, relict), are common and remind us that the commonly held perception of a lagoon as a quiet-water environment is at least deceptive, if not erroneous. Halos of unvegetated white sand develop around objects (reefs, rocks) because of the grazing action of organisms. After a few minutes of flying, the enormous size of this central portion of Great Bahama Bank becomes evident.

Elongate patches of milky water (about 1 km long) can sometimes be seen. These are termed "whitings" and are isolated areas of turbid water containing suspended sediment (Shinn and others, 1989). The origin of the sediment is either by inorganic precipitation within the water column (which has not yet settled) or by resuspension from the bottom (by fish or some other physical activity).

Eastern margin

As we approach the eastern margin of Great Bahama Bank, we again come upon shallow sand shoals, reefs, and islands. We will fly either over the tidal flats on the west side of Andros Island or Joulters Cays, an ooid shoal north of Andros Island (fig. 3).

Andros Island

Andros Island is the largest island in the Bahamas (160 km by 60 km). The large tidal flat (about 10 km wide by 100 km long) on the west side has been the site of numerous investigations (Shinn and others, 1969; Hardie, 1977; Shinn, 1983; Hardie and Shinn, 1986). Blue holes (vertical shafts with rounded surface expressions created by dissolution) dot the interior of this very flat island (Palmer, 1985). Most (about 90 percent) of the island is less than 5 m above sea level. The highest elevation (20 m) of this portion of the Bahamas is located on the eastern margin of the northernmost promontory of Andros Island (Morgan's Bluff). Andros is the major source of water for New Providence Island and its capital city, Nassau, the tourist center and most populous area of the Bahamas. The island has been logged, and logging trails, which are visible from the air, are arranged in a rectilinear fashion over much of the interior of the island. The major towns on Andros are all located on the eastern side with the exception of Red Bay, located in the northwest. Nichollstown is located in the northeast a few kilometers south of Morgan's Bluff. Farther south are Mastic Point (due east from the San Andros airport), Stafford Creek and Staniard Creek. The town of Fresh Creek is located about 60 km south of Morgan's Bluff and is the home of AUTEC (American Undersea Testing and Evaluation Center) directed by the U.S. military, and Androsia, where hand-dyed (batik) material and clothing are made.

Joulters Cays

Joulters Cays is a Holocene ooid sand shoal with three major islands, channels, flood- and ebb-tidal deltas, a large intertidal sand shoal, shallow stabilized sand flats, and reefs (seaward of the islands; fig. 4). This ooid shoal is commonly used as a modern analog for ancient oolitic sequences because its facies distribution, depositional history, and diagenesis are better known than other ooid shoals (Harris, 1977, 1979, 1983; Halley and Harris, 1979; Halley and others, 1983).

Berry Islands

The Berry Islands are an arcuate string of islands located north of Joulters Cays. Like Joulters Cays, the islands are Holocene in age, and much of the sediment in the inlets and surrounding the islands is oolitic.

Tongue of the Ocean

To the east of Andros and Joulters Cays is Tongue of the Ocean, one of the deep (3,000 m) oceanic re-entrants or channels that separate portions of the Bahamian platforms. Like the western margin of Great Bahama Bank, the drop-off here is steep.

New Providence Island

Nassau, the capital of the Bahamas, and "Paradise Island," the site of popular hotels and casinos, are located on New Providence Island. New Providence consists of Pleistocene carbonates primarily in the form of eolian dunes and beaches (Garrett and Gould, 1984).

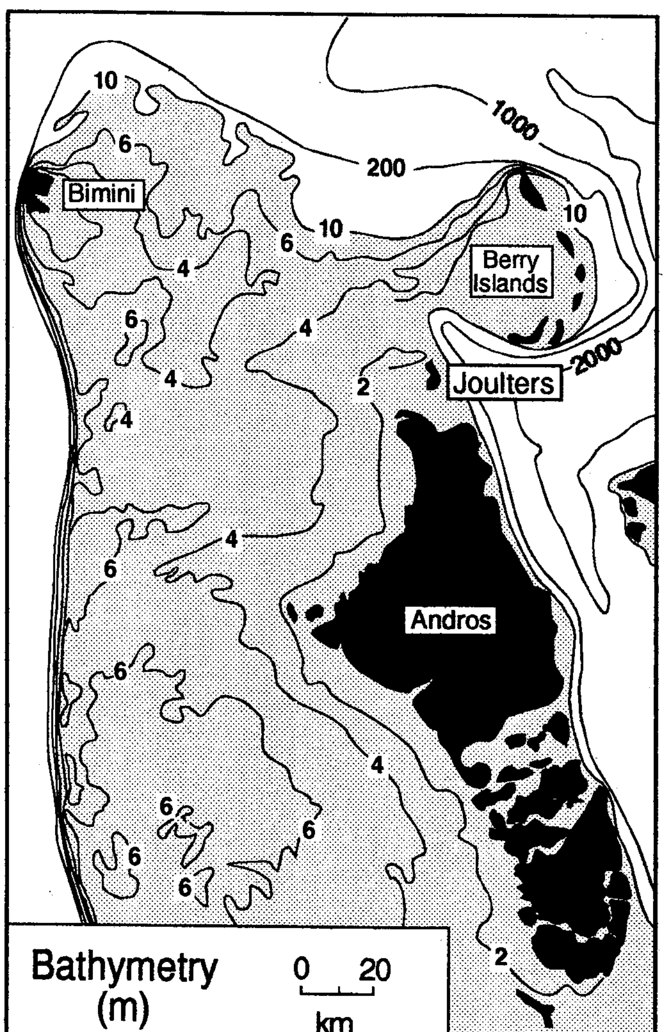


FIGURE 2.—Bathymetry of Great Bahama Bank (after Gebelein, 1974). Most of the platform is less than 5 m deep (area of pattern).

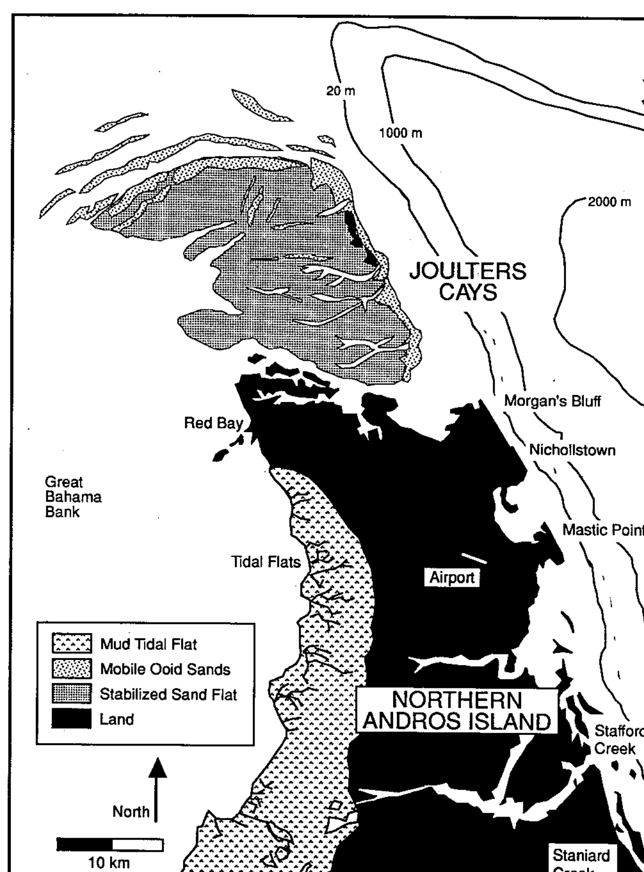


FIGURE 3.—The eastern margin of Great Bahama Bank includes Andros Island and Joulters Cays.

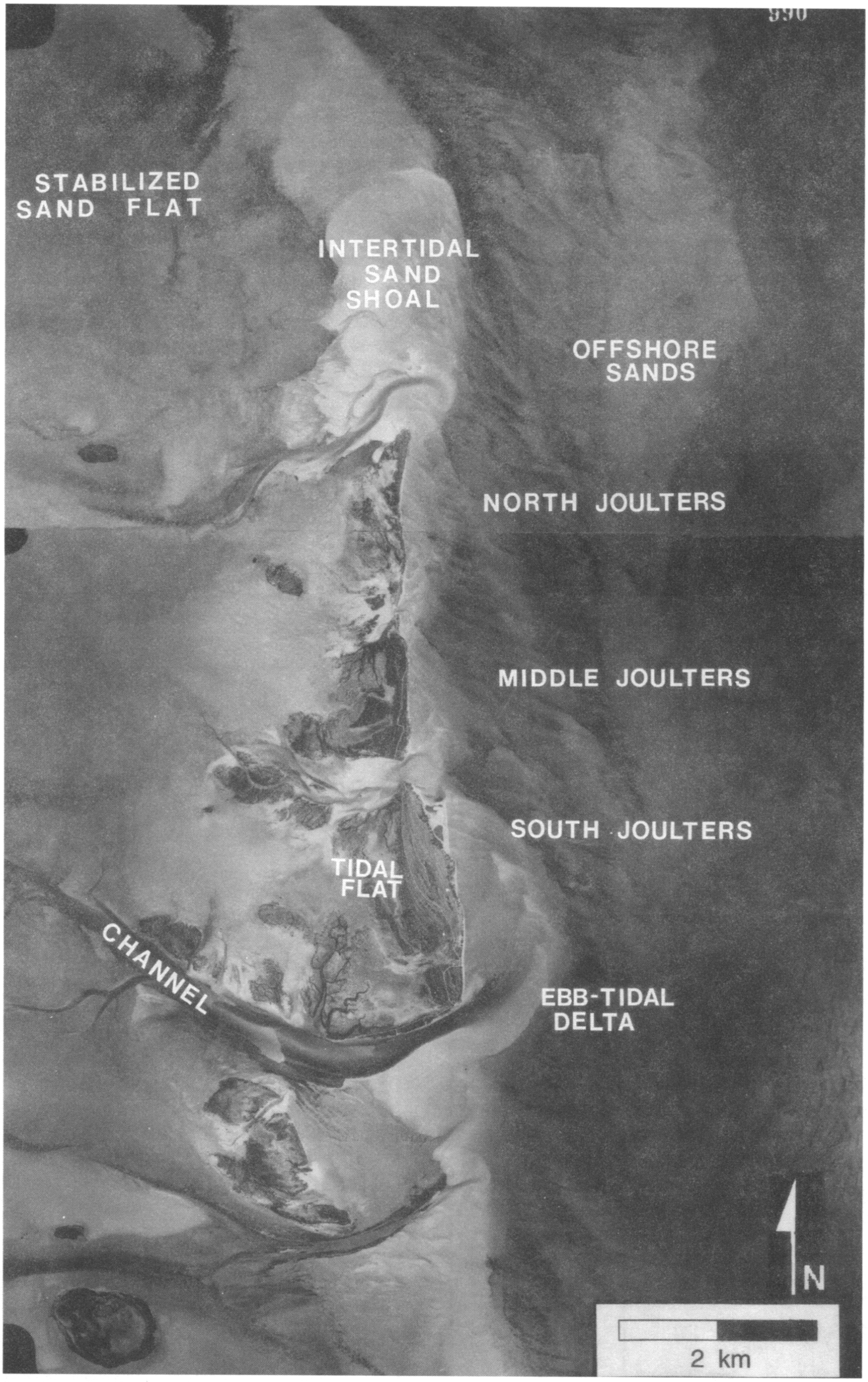


FIGURE 4.—Aerial photograph of Joulters Cays, a Holocene ooid sand shoal complex (1967; original scale 1:40,000).

Schooner Cays

Schooner Cays is a large ooid sand shoal on the re-entrant margin west of the island of Eleuthera. It consists of linear tidal bars and channels oriented at a high angle to the bank margin (Dravis, 1979). This geometry is typical of ooid shoals in regions of high tidal currents (relative to wave energy and longshore transport). Behind (to the north of) Schooner Cays is a large open lagoon similar to that of Great Bahama Bank.

Eleuthera Island

Eleuthera ("the wanderer") Island is an arcuate island primarily composed of Pleistocene eolian dunes. There are several towns on this island. A Club Med resort is located on the southern end.

Cat Island

Like Eleuthera, Cat Island is composed of Pleistocene eolian ridges. The highest point in the Bahamas (over 60 m) is on Cat Island.

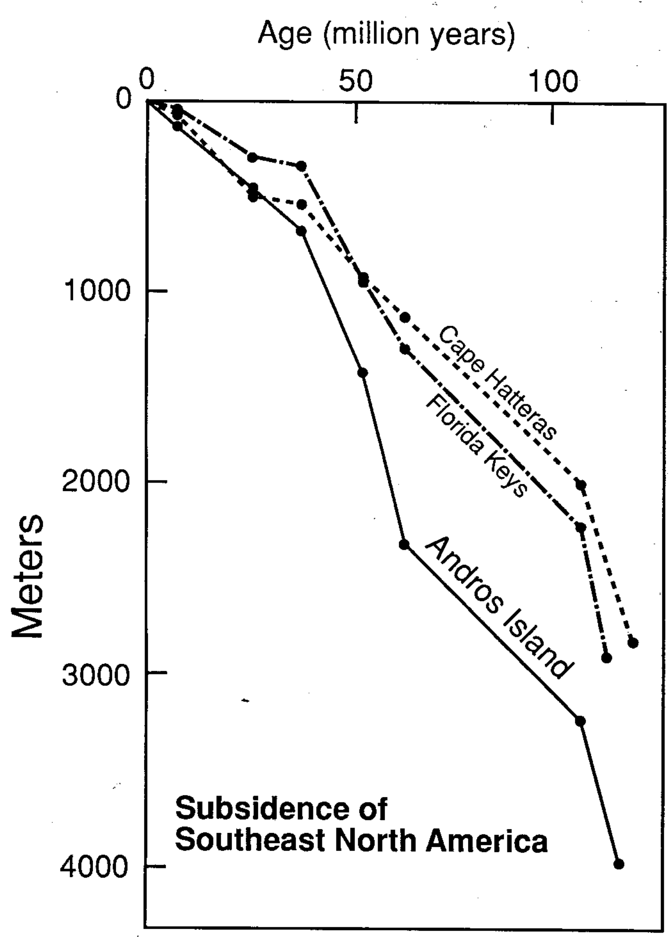


FIGURE 5.—Subsidence of Great Bahama Bank (Andros Island) is approximately the same as that of Florida and the east coast of North America (from Mullins and Lynts, 1977).

Atlantic Ocean

Between Cat Island and San Salvador, the Atlantic Ocean reaches oceanic depths (> 4,000 m). As we leave Cat Island behind us, San Salvador can usually be seen in the distance, under a layer of clouds.

San Salvador

As we approach San Salvador, we will cross over the platform edge (the drop-off), which is generally in about 20 m water depth, and fly for a few seconds over the shallow marine open lagoon. The drop-off is very near the margin of this island. The end of the runway (which is paved) on San Salvador is only a few meters from the ocean and only a couple of meters above sea level. The airport was built as part of a U.S. military buildup (Navy, Air Force, and Coast Guard) to take advantage of the strategic location of San Salvador.

ORIGIN OF THE BAHAMAS AND UNDERLYING GEOLOGY

Geophysical evidence suggests that the Bahamas are underlain by up to 10 km of sedimentary rock overlying "basement" (Mullins and Lynts, 1977). This evidence, coupled with coring, indicates that more than 4 km of shallow-water limestones and dolomites of Cretaceous to Holocene age are present (Spencer, 1967; Goodell and Garman, 1969). However, the sedimentary units below the shallow-water limestone as well as the crust (continental or oceanic) beneath the Bahamas are poorly known.

The high relief of the platforms may be the result of horst and graben structures created during the initial formation of the Atlantic Ocean (Mullins and Lynts, 1977). Additional relief may have been created because of the difference in rates of deposition between the shallow-water platforms (initially horsts) and the deep-water re-entrants or channels (initially grabens). Since the Cretaceous, subsidence has been 1-4 cm/1,000 years (10-40 m/million years) (fig. 5). During the past few million years, subsidence of Great Bahama Bank has been about 1.5 to 2 cm/1000 years. Comparisons with other banks suggest that subsidence varies slightly between platforms (Pierson, 1981).

Using the Pleistocene as an example of sea-level fluctua-

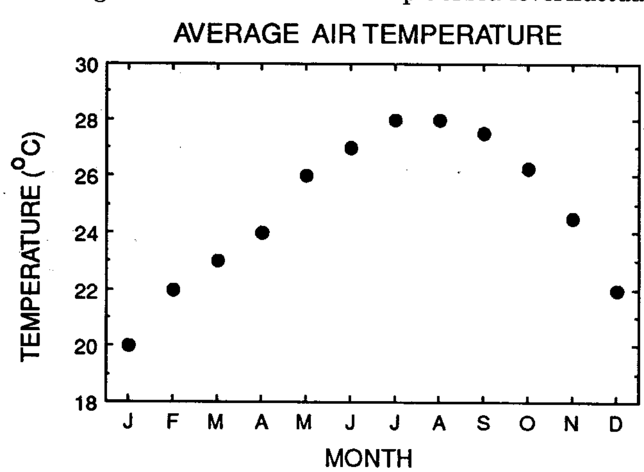


FIGURE 6.—Average annual fluctuation of temperature of Andros Island, Bahamas (after Gebelein, 1974).

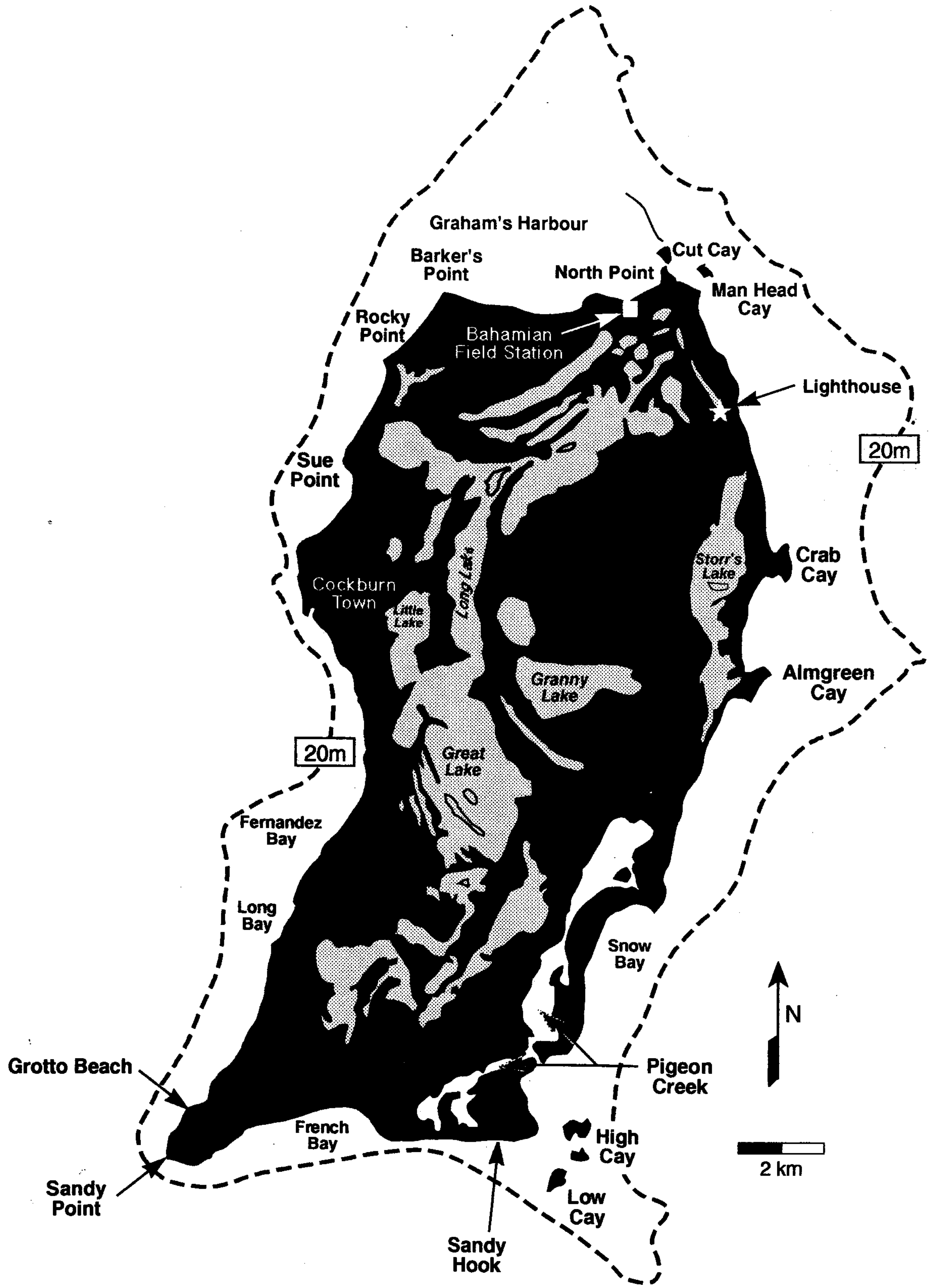


FIGURE 7.—Map of San Salvador. Most of San Salvador consists of Pleistocene arcuate dune ridges and swales. Many of the swales are now near, or below, sea level and form inland lakes.

tions (and who knows better than that?), one concludes that the platforms were only flooded for a few thousand years every 100,000 years (~5 percent of the time), and one might expect that the continuous deposition in the deep-water channels would cause the channels to fill. However, the rate of pelagic sedimentation in the inter-platform channels is approximately 1/20 (5 percent) that of the platforms (1-4 cm/1000 years versus 20-100 cm/1000 years). Thus, the relative depths of the platforms and channels are poised at some steady state. This steady state of relief can be upset if there is substantial off-bank transport of sediment. Studies of near-platform sediment accumulation confirm that substantial off-bank transport occurs (Hine and others, 1981; Boardman and Neumann, 1984; Boardman and others, 1986; Wilbur and others, 1990). On the basis of seismic surveys, it is now known that Great Bahama Bank was divided into several platforms during the Miocene and that the channels dividing the platforms have been filled with sediment, presumably shallow derived (Eberli and Ginsburg, 1987).

ENVIRONMENTAL PARAMETERS

The Bahamas exist in a "normal" tropical marine environment. Air temperature generally fluctuates seasonally from 20 to 28°C (fig. 6), and extremes include rare near-zero air temperatures. Water temperatures are generally 22 to 30°C; however, the temperature of local pools and channels of water can be 50°C. The weather of the Bahamas is influenced by the regional pattern of trade winds, which blow from the northeast and east at about 20 km/hr. This regional wind pattern is punctuated by storm winds of 200 km/hr (hurricanes), which have no predictable general direction. The wind direction of hurricanes is counterclockwise around the eyes. Thus the wind direction experienced by any location depends on the storm path. Storm frequency is eight per 10 years (Hine, 1977). Cold fronts, which also contain high winds, are even more frequent.

The salinity of the waters surrounding the platforms is normal marine (approximately 36‰), but on the platform interiors (*e.g.*, Great Bahama Bank) fluctuations from the norm can occur. The shallow depths and high evaporation result in elevated salinities if water exchanges between the platform interiors and off-platform areas is insufficient to keep salinities near normal. It seems reasonable to expect that slightly lower salinities could also be obtained during intense rainfall.

OVERVIEW OF THE GEOLOGY OF SAN SALVADOR

San Salvador Island (fig. 7) is a small island (approximately 20 km by 10 km) located just above the Tropic of Cancer (24° N lat., 74°30' W long.). It is entirely composed of carbonate sediments of Holocene and late Pleistocene age. There are excellent overviews of the surficial geology of San Salvador (Adams, 1980; Gerace, 1980; Carew and Mylroie, 1985, 1987). Specific details of the geology also are included in previous guidebooks to San Salvador Island (Curran, 1985, 1989), as well as in the various Proceedings of Symposia on the Geology of the Bahamas (Teeter, 1984; Curran, 1987; Mylroie, 1989; Bain, 1991).

The general pattern of the geology of San Salvador includes a core of arcuate Pleistocene eolian dunes 20 to 30 m high and composed of oolitic, peloidal, and bioclastic grains. Lakes of variable salinity separate the dunes. Late Pleistocene reefs, subtidal sands, and beaches are also present. In addition to exposures of late Pleistocene rocks, the outer portion of the island includes unconsolidated and consolidated Holocene strand plains and beaches. High linear dunes, which formed in the early Holocene, are located on the windward (eastern) margin and are presently being eroded.

The subaerial portion of San Salvador occupies the bulk of the platform. The subtidal portion is narrow and contains barrier reefs, patch reefs, high-energy lagoons and subtidal sands. Low-energy marine sediments are found in a narrow, linear lagoon on the southeastern portion of the island (Pigeon Creek). The edge of the platform (the drop-off) is close to the island at water depths of 20 to 30 m.

ITINERARY

Our base of operations for the field trip will be the Bahamian Field Station located on the northern coast of San Salvador (fig. 7). The following is a synopsis of the planned itinerary:

Day 1: Morning - Arrive on San Salvador; North Point eolian dunes
Afternoon - Graham's Harbour lagoon snorkel

Day 2: Morning - In the footsteps of Columbus (boat trip)
Afternoon - Reefs (snorkel or dive)

Day 3: Morning - Pigeon Creek lagoon
Afternoon - Sandy Hook strand plain, Grotto Beach

Day 4: Morning - Return to Florida
- Joulters Cay optional field trip

THE HOLOCENE CARBONATE EOLIANITES OF NORTH POINT AND SOME NEARBY MARINE ENVIRONMENTS, SAN SALVADOR ISLAND, BAHAMAS

by
Brian White and H. Allen Curran

The goals of this part of the field trip are to study the types of strata, sedimentary structures, trace fossils, and dune morphologies of the Holocene eolianites excellently exposed along the coasts of Rice Bay and North Point. Here, the mechanisms of how eolian deposition of carbonate grains occurs and how dunes are initiated and evolve are well illustrated in the rocks. Toward the end of this excursion, a short snorkel dive can be conducted in the shallow, sheltered waters between North Point and Cut Cay to study grass beds, sandy substrates, and hard substrates and to compare their associated sediments, plants, and animals. The area to be visited and the locations of field stops are shown in figure 8.

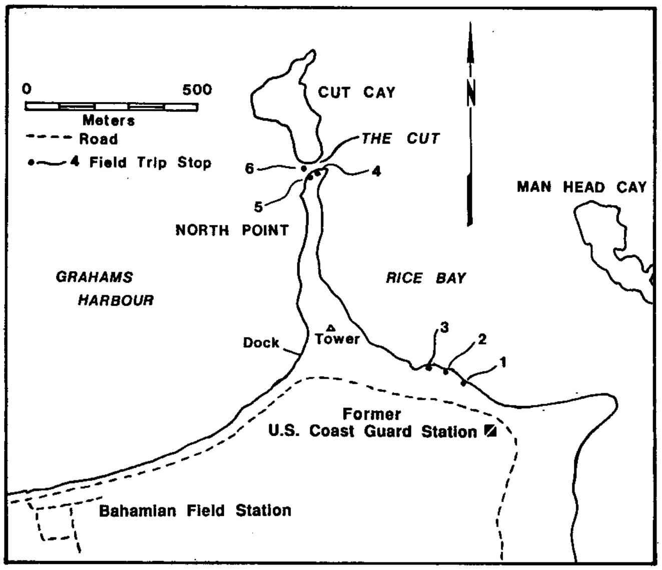


FIGURE 8.—Map of North Point area and locations of described stops.

PREVIOUS WORK

Adams (1980), in his pioneering study of the geology of San Salvador, briefly described the eolianites of North Point. He distinguished lobate dunes that have large-scale cross-beds on their leeward faces and flanks and smaller, more varied, cross-beds on their windward slopes. In their overview study of the petrography of the eolianites of San Salvador, Hutto and Carew (1984) found that most are dominantly oolitic. However, their North Point samples, had a higher proportion of skeletal grains and pellets. The North Point eolianites were assigned to the North Point Member of the Rice Bay Formation by Carew and Mylroie (1985). Samples of North Point Member rocks from North Point gave radiocarbon dates of 5,345 ± 125 and 5,360 ± 110 years B.P. (Carew and Mylroie, 1987).

In her more detailed study of the eolianites of the Rice Bay area, Lawlor (unpublished data, 1985) found that these rocks are pelsparites with lesser proportions of ooids and skeletal grains. The rocks are dominantly aragonite with incomplete cementation by vadose low-Mg calcite. Inverse-graded bedding is a common feature of the rocks on a microscopic scale; cementation is somewhat more complete in the finer layers (White and Curran, 1988). More recently, White and White (1991) have shown that these eolianites do bear evidence of diagenesis from the ongoing episode of Holocene marine transgression.

EOLIANITES OF THE RICE BAY TO NORTH POINT AREA

The Holocene dunes of this area are composed of carbonate sand which was blown landward from marine beaches by onshore winds. Initially, small dunes developed landward of the beach, a few around cores formed of the eroded remnants of earlier dunes. In some cases two small adjacent dunes were enveloped by later dune sediments to form a compound dune. Elsewhere, dunes grew higher and migrated inland as individual lobes, with slip faces sloping not only downwind, but to the right and left on the flanks of each lobe. Eventually, the lower parts of the flanks of adjacent dunes overlapped to cover the interdune areas and thereby form a long, hummocky dune ridge. This dune morphology is clearly reflected in the undulating topography of the west side of North Point as seen from the campus of the Bahamian Field Station.

Large-scale, steeply dipping cross-beds occur on many lee slopes and flanks of the lobate dunes. Windward dune slopes reveal a greater variety in scale and type of cross-bedding, including examples of tabular-planar, wedge-planar, and trough sets. The latter are more numerous in the lower parts of the dunes. Wind ripples are visible on some bedding surfaces, but they are scarce. In some of the cross-bedded exposures, it is possible to distinguish the different strata produced by climbing wind ripples, grainfall, and sandflow as described from modern coastal dunes by Hunter (1977).

Although fossil burrows previously have been thought to be rare in eolianites (McKee and Ward, 1983), there are several large and well-preserved burrows and numerous smaller burrows here, all thought to have been formed by invertebrates in dunal sands that now are the eolianite exposures along Rice Bay (White and Curran, 1988). Rhizomorphs, trace fossils produced by plant roots, are common in these eolianites. An overview of the significance of this trace-fossil assemblage was given by Curran and White (1991).

DESCRIPTIONS OF THE FIELD STOPS

The beach in front of the former U.S. Coast Guard Station makes a convenient starting point for this trip. From here the view extends northeast over the sandy beach and across the waters of Rice Bay to Man Head Cay. To the northwest (left), some of the North Point eolianite exposures can be seen. The first of these are reached by walking about 90 m along the beach in a northwesterly direction.

Continuous exposures of Holocene dunes in sea cliffs and on narrow, rocky shore platforms along this reach of coast reveal numerous features of the eolianites. The stops described below were selected to demonstrate particularly good, and readily accessible, examples of trace fossils, sedimentary structures, and stratum types found in the eolianites, and of dune morphology. After walking about 1 km along the peninsula, the end of North Point is reached, where final observations of the dunes can be made. The small beach on the west side of the point is a good place to begin a snorkel dive to view the nearby hard substrates, *Thalassia* grass beds, and sandy substrates and to examine their associated sediments, flora, and fauna.

Stop 1. Cluster-burrow trace fossil type locality

To reach this stop, walk northwest along Coast Guard Beach to the first rock exposures and then continue over outcrops and a small sandy bay for 60 m. Here sea cliffs 3 to 4 m high are cut into an 85-m-wide fossil dune. Along much of this dune's width, cross-bed dip directions are rather variable, but generally towards the southwest, and dip angles range from almost flat-lying to 15°. On the northwest flank of the dune, dips are northwesterly and steepen to 30°, with some sandflow cross-strata evident. At the southeast end of the dune, steepening cross-strata dip

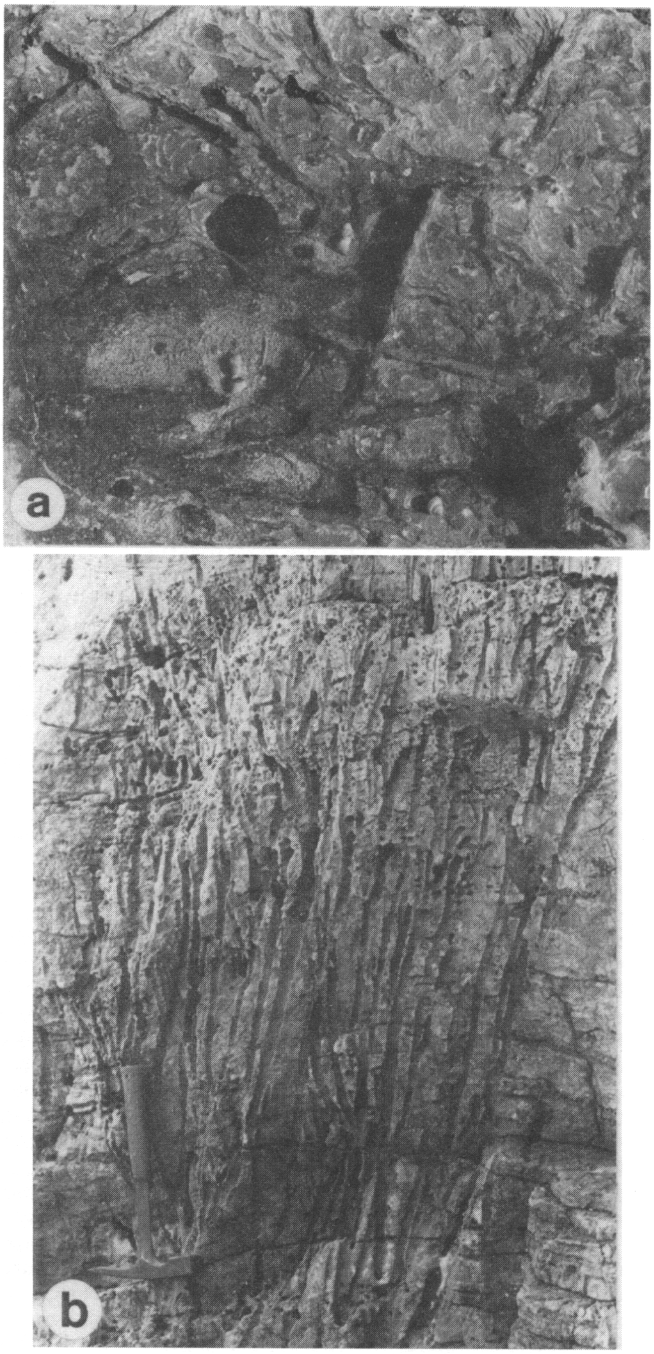


FIGURE 9.—**A**, rhizomorphs on an eolianite bedding surface, Stop 1. Lens cap is 5 cm wide. **B**, vertical, straight to gently curved, unlined shafts of the cluster-burrow trace fossil at Stop 1. Burrow shafts are up to 1.4 m in length; about 45 closely spaced shafts occur in this exposure. Hammer is 30 cm long.

to the south at angles of up to 20°. Most of the strata are in small wedge-planar sets, suggesting variable wind directions, and climbing wind-ripple strata are evident in some places.

A prominent trace fossil consisting of a cluster of vertically oriented burrows is exposed in a small cliff face here and in a large counterpart block that has fallen away from the cliff. The trace fossil cuts vertically across 1.4 m of small-scale, wedge-planar and trough-cross-strata sets, which are obscured in places by bioturbation. Fine, millimeter-scale laminations are evident on much of the cliff face, and weathered surfaces reveal some very thin laminations of slightly coarser calcarenite. In the rocks immediately overlying this trace fossil, rhizomorphs are prominently displayed on some bedding planes, where they weather out in relief (fig. 9A).

In detail, this trace fossil consists of multiple, straight to gently curved, unlined shafts. Shaft diameters are 1 to 2 cm (average 1.3 cm), and shaft lengths can be at least as long as 1.4 m (fig. 9B). This is a minimum length for the shafts of this specimen because a break in the cliff face in which it is exposed terminates the lower part of the specimen. Some shafts branch in the upward direction, and some definite cross-overs also occur. Shaft diameters tend to contract somewhat toward their upward ends.

The clustered nature of the shafts and their large number suggest that the structure records the brooding/hatching activity of an invertebrate organism, very possibly a species of burrowing (digger) wasp of the Family Sphecidae. The shafts were formed by the juvenile wasps burrowing up to the surface. This hypothesis was discussed in some detail by Curran and White (1987).

About 50 m northwest of the trace fossil just described, a similar one is exposed in horizontal cross section. Here the circular nature of the cluster and the large number of individual burrows (about 800 shafts) that it contains are clearly revealed. Here, too, this trace fossil is within a sequence of small-scale, wedge-planar and trough-cross-strata sets, which have scattered rhizomorphs and climbing-ripple laminations. Of additional interest is a small bedding surface at least 1 m below the cluster trace fossil and within the present-day intertidal zone. On this bedding plane there are ripple marks with crests oriented perpendicular to the strike of the bedding plane, a feature believed to indicate an eolian origin (McKee and Ward, 1983). The ripples have a very low amplitude and ripple indices of 25 to 30, further evidence that they are wind-formed ripples (McKee, 1979; Tanner, 1967). Two interesting conclusions may be drawn from these observations. As the wind-deposited strata are located in the present intertidal zone, it is clear that sea level was lower at the time of formation of these beds than at present. The presence of wind-formed ripples beneath the trace fossil confirms that the burrowing took place in an eolian dune and not in a beach or nearshore environment.

Stop 2. Fossil proto-dunes on rocky shore platform

This next locality is reached by dropping down the northwest flank of the dune at Stop 1 to a broad, rocky shore platform, some 80 m long and up to 20 m wide, backed on its landward side by low cliffs and extending seaward into the intertidal zone. Because of the extensive horizontal and vertical exposures, this is an excellent place to study sedimentary structures and the early stage of dune development.

In the landward cliffs, several small dune cores are exposed (fig. 10A). Some of these are better lithified and contain more abundant rhizomorphs than overlying strata and appear to be the eroded remnants of earlier dunes. Large-scale trough cross-beds immediately adjacent to some of the dune cores (fig. 10B) may have formed by wind scouring around the dune remnants. Subsequent deposition of wind-blown sand buried the dune cores and the growing dune extended laterally and vertically to encompass them into a form of compound dune.

Other sedimentary structures well-displayed here are

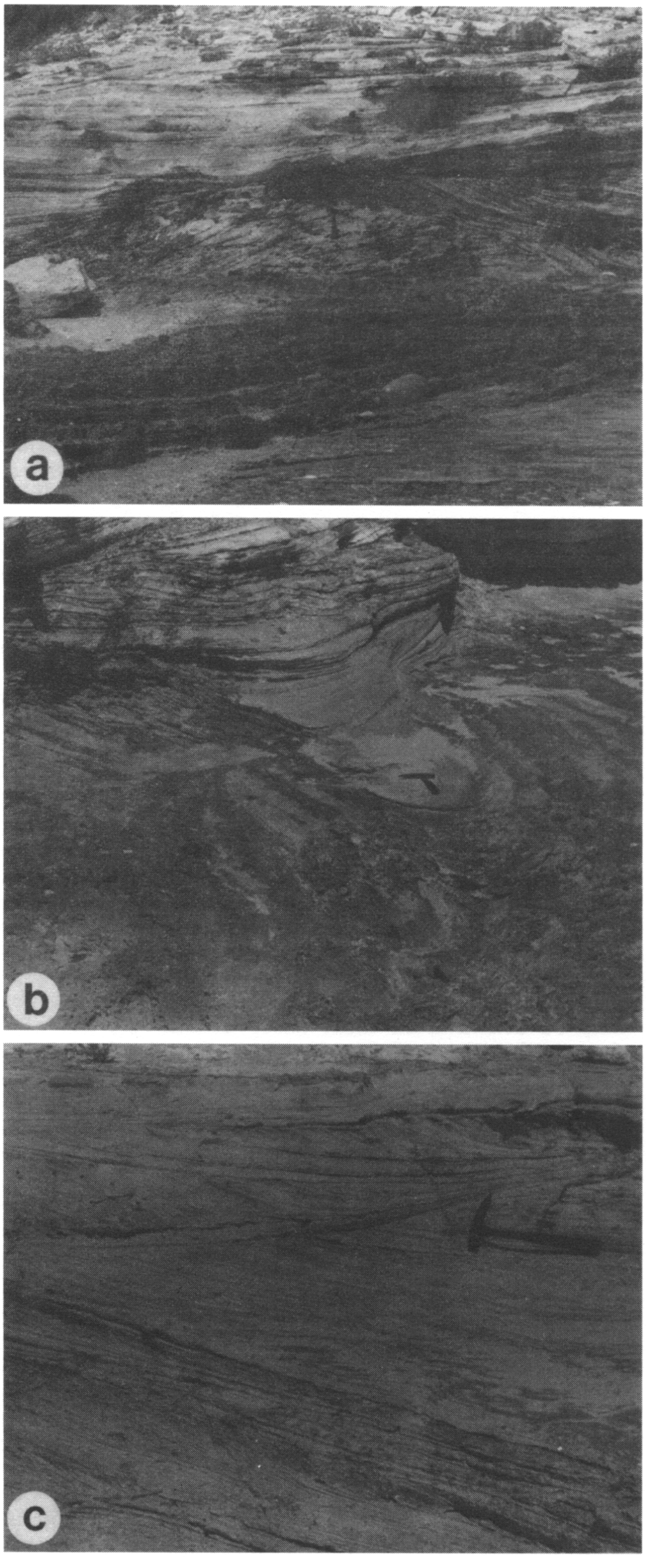


FIGURE 10.—**A**, eroded remnant of an older dune overlapped by younger eolian strata, Stop 2. **B**, trough cross-beds adjacent to an older dune core at Stop 2. **C**, wedge-planar cross-bed sets showing tangential relationship to underlying strata, Stop 2. Hammer in all photos in 30 cm long.

convex-upward cross-strata sets, trough cross-beds, and wedge-planar sets. Some of the latter have cross-strata with acute angular relationships to the underlying set; whereas others show a tangential relationship (fig. 10C). Several bedding surfaces have ripple marks with ripple indices between 23 and 32, clearly wind ripples (McKee, 1979; Tanner, 1967). Again, some of these are within the present intertidal zone, confirming the conclusions drawn at Stop 1 about lower sea level at the time of eolianite deposition.

Beyond the rocky terrace of Stop 2, follow the coast as it takes a short jog to the west, then cross a 30-m-wide bay with a sand and rock floor to reach another promontory. Scramble down the northerly side of this headland and traverse the narrowing beach for about 40 m, until a small rock arch is reached. Progress along here will be blocked at some point, exactly where depending on wind conditions and the state of the tide. In any case, from the vicinity of the small arch, climb upward obliquely across the cliffs to a small gully, which constitutes the next stop.

Stop 3. Eolianite stratification

Exposed in proximity at this locality are three types of wind-deposited strata that were produced by mechanisms described by Hunter (1977, 1981) as grainfall, sandflow down lee slopes, and climbing wind-ripples (fig. 11A). The strata produced by climbing wind-ripples are millimeter laminations with even thicknesses and sharp contacts resulting from inverse size grading, although the latter detail is not always readily visible in the field. If net sedimentation is to occur by the migration of wind-ripples, then each successive ripple must climb relative to the stratum deposited by the previous one. Grain size segregation in wind-ripples concentrates relatively coarse sediment on the crests and relatively fine sediment in the troughs. As the crests and troughs migrate, they deposit a layer of relatively coarse grains overlying a layer of relatively fine ones; hence the upward size grading within each stratum produced during deposition by a migrating wind-ripple. Wind-ripples may climb up, down, or along both lee and stoss sides of dunes. Thus the dip angle and direction of the resulting strata are more a function of the geometry of the surface over which they have migrated than the direction of the driving wind. The passage of many wind-ripples can lead to the accumulation of sets of ripple-formed strata. On lee slopes these strata may be preserved under grainfall sediments or sandflows, providing the latter are not erosive.

Grainfall occurs when moving air currents carry saltating and suspended sediment into a sheltered area, for example, the zone of separation to the lee of a dune crest. The sediment settles like falling snow and accumulates on the lee slope of the dune, where it may be joined by grains that crept over the dune crest in response to collisions with saltating grains. Grainfall strata tend to be thin and indistinct, and, because they commonly form on lee slopes, they generally have a high initial dip (Hunter, 1981). On small dunes, though, grainfall could occur as far forward as the toe of the dune, and the strata would lie at low angles. In wind-tunnel experiments conducted by Fryberger and Schenk (1981), grainfall strata deposited on lee slopes consistently wedged thinner downslope, and this wedging may be anticipated on natural dune lee slopes as well.

Sandflow strata form by resedimentation of sands that accumulate on the upper part of lee slopes, commonly by grainfall, until the slope oversteepens and becomes unstable. If the sands are dry, they will flow noncohesively, but, if they are crusted or partially lithified in some way, they may founder as blocks subject to all kinds of jumbling and deformation. Sandflow strata are typically thicker than other wind-deposited strata, commonly exceeding 1 cm. They have sharp contacts, lie close to the angle of repose, and tend to pinch out towards the base of a foreset (Hunter, 1981). They have a distinctive lenticular shape in strike cross section or in horizontal exposure (fig.11B).

These types of wind-formed strata were recognized by studying modern coastal dunes (Hunter, 1977). Several attempts have been made to use these strata to identify and more closely characterize ancient siliciclastic rocks believed to be of eolian origin. Such studies include: Pleistocene of Oregon (Hunter, 1980); Permian of Arran, Scotland (Clemmensen and Abrahamsen, 1983); and various Paleozoic and Mesozoic formations of the western United States (Fryberger and Schenk, 1981; Hunter, 1981). Prior to this study, similar analyses do not seem to have been reported for carbonate rocks, and these various wind-deposited strata are not mentioned by McKee and Ward (1983) in their review of carbonate eolian environments.

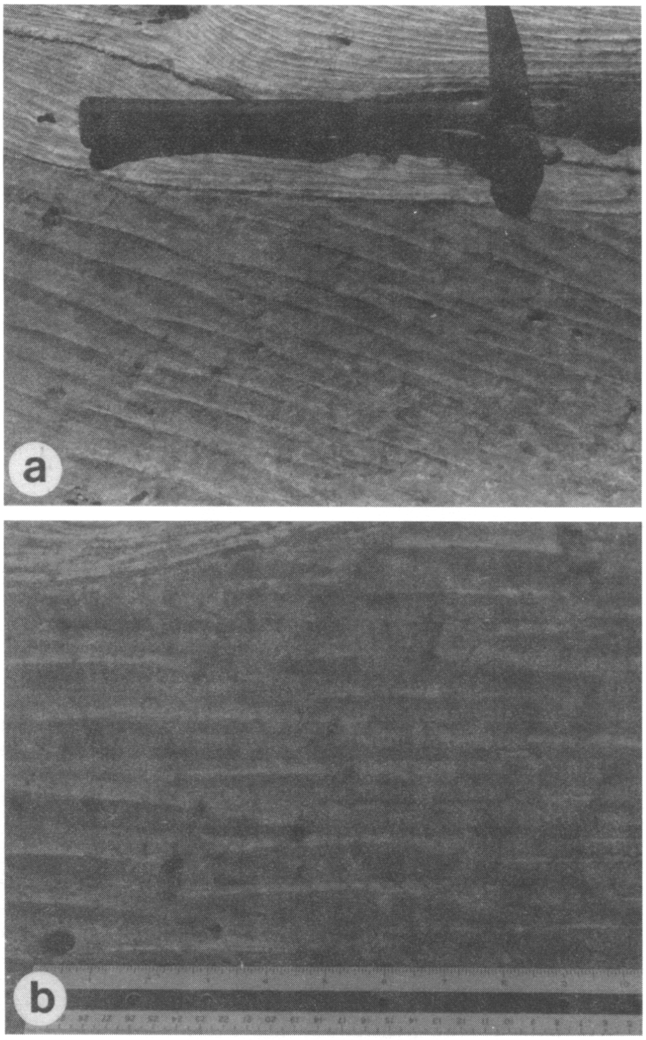


FIGURE 11.—**A**, sandflow strata within grainfall strata at Stop 3; both types are overlain by wind-ripple-formed strata. Hammer is 30 cm long. **B**, lenticular sandflow strata within grainfall deposits, Stop 3. Ruler for scale.

Small, irregularly meandering burrows 3 to 4 mm in diameter and reaching greater than 20 cm in length occur within and upon grainfall and sandflow strata in the North Point Member eolianites (White and Curran, 1988). Examples of these trace fossils are common in the vicinity of Stop 3. We suggest that these burrows also probably were formed by insects or insect larvae, but a specific modern trace-maker analog for this burrow type has not yet been identified. Recently, we have found similar small, irregular burrows and cluster burrows in Holocene eolianites on Lee Stocking Island of the Exuma Cays.

To continue this field trip, stay at the top of the sea cliffs and walk around the small bays and headlands for about 200 m. Hereabouts a more prominent trail joins from the south, and the wreck of a tanker scars the coast to the northeast. Follow the winding trail northward along the spine of the narrowing peninsula. Along the way one will pass many exposures of eolianites, and one can enjoy fine views to the west (left) over Graham's Harbour and to the east over Rice Bay and Man Head Cay. About 400 m beyond the wreck is the edge of a cliff that overlooks a tidal inlet and an island to the north. This is the next field-trip locality.

Stop 4. Cut Cay overlook

Here, at the north end of North Point, the cliffs are formed by the north flank of a well-developed lobate dune, and the cross-bedding dips north and steeply down into the sea. A 40-m-wide inlet, The Cut, separates North Point from the nearby island of Cut Cay. The cliffs of the south end of Cut Cay are part of the south flank of another dune, and the cross-bedding dips down into the sea on that side too, but in a southerly direction. Evidently, the sea has driven through along a low interdune area and separated Cut Cay from the rest of the peninsula. According to legend, The Cut did not exist at the time of Columbus' visit in 1492.

From this location a good view of the seafloor to the west out into Graham's Harbour and to the northwest towards Cut Cay can be obtained. This perch provides an excellent overview of the three different substrates which are easily explored by snorkeling in this calm (usually) water. The dark-green grassbeds are dominated by *Thalassia*, the pale-green areas are sandy bottoms, and the tan areas are hard substrates. Calcareous green algae, including *Halimeda, Penicillus, Udotea*, and *Acetabularia*, grow in the grassy and sandy areas. Their abundance and distribution vary from time to time, perhaps seasonally. A considerable variety of invertebrate animals lives among the various plants of these different environments and awaits careful and sharp-eyed explorers.

Following this preview, climb down the west side of North Point by taking the only obvious (and safe) route to the small beach. This is the location of the next field-trip stop and the starting point for the snorkel dive.

Stop 5. Dune morphology revealed in sea cliffs

A number of well-developed lobate dunes are clearly exposed in the cliffs on the west side of North Point (figs. 12A and 12B). Here the dunes have reached a more mature stage of development than some seen along Rice Bay. The opposing flanks of each dune dip steeply and in opposite directions. Along this part of the coast the relationships between adjacent dunes are revealed. In some cases, one dune flank overlaps the flank of the nearest dune, suggesting that the former was mobile and the latter stabilized, at least temporarily. In other situations, adjacent dune flanks interfinger and both dunes appear to have been mobile. This entire coastline is made up of a row of these coalesced lobate dunes that is clearly visible from the vicinity of the Bahamian Field Station, especially when illuminated by the setting sun. Dune lobes that coalesce to form such a transverse dune ridge have been described from Pleistocene carbonate rocks of other parts of the Bahamas by Ball (1967) and from Bermuda by MacKenzie (1964a, 1964b).

The fact that wind-deposited cross-beds dip down into the sea here at North Point is further evidence that these eolian dunes formed before sea level rose to its present position. Additionally, such evidence shows that the wind-blown sands were sufficiently lithified by the time sea level rose to resist simple reworking of the sand.

ACKNOWLEDGMENTS

We thank the staff of the Bahamian Field Station for full logistical support of our field work on San Salvador. Valuable contributions to the North Point research project were made by Smith College geology majors: Liz Dole, Kate Japy, Karen Kurkjy, Jean Lawlor, Kim Pirie, and Kathy White. Acknowledgment is made to the donors of the The Petroleum Research Fund, administered by the American Chemical Society, for partial support of our work through separate grants to Curran and White. Generous financial support also was provided by the Merck, Keck, Pew, and Shell Foundations, and we extend our thanks to each of them.

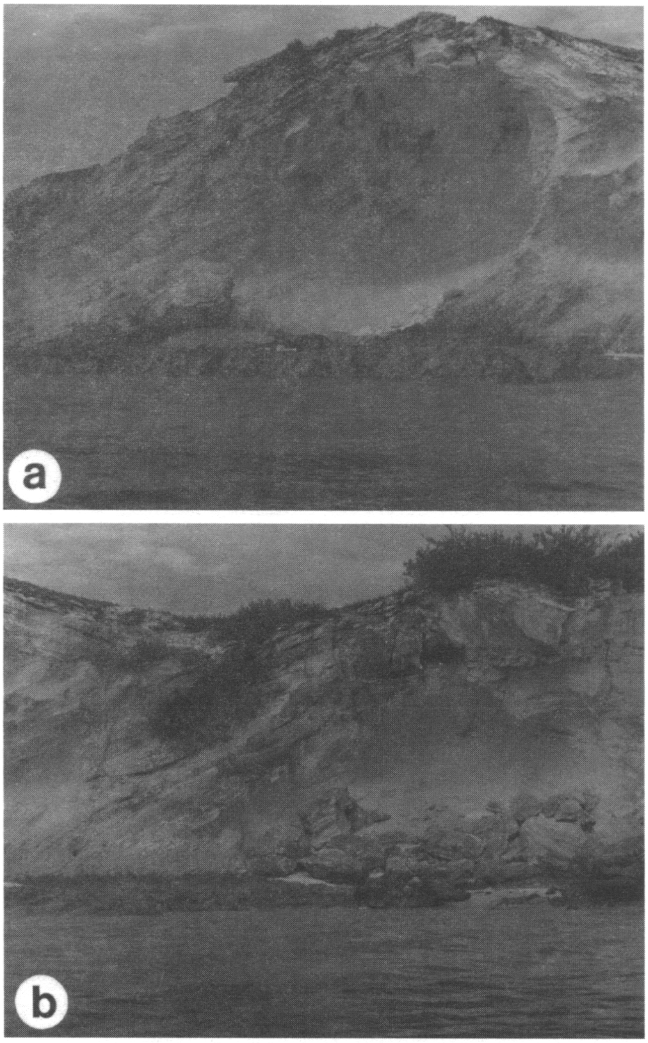


FIGURE 12.—**A**, view from the west of lobate dune forming the north end of North Point, Stop 5. **B**, view from the west of lobate dune immediately to the right (south) of the dune shown in 12A.

GRAHAM'S HARBOUR SNORKEL

Graham's Harbour is a shallow carbonate lagoon on San Salvador (figs. 7, 13). To the east and northeast, Graham's Harbour is protected from waves by a barrier reef and by linear eolian dunes. Waves from the north and west may exert greater control over benthic communities and the pattern of sedimentation. The lagoon has been the site of numerous research projects which should provide useful analogs for ancient lagoonal sequences. Current research includes a study of lateral and temporal patchiness of seagrass growth, mollusc communities, and sediment characteristics. In addition, sediment sources, mixing, and transport are being studied by petrographic means.

What is a lagoon? A lagoon is a body of shallow water which is restricted in some manner from the open ocean. One stereotypic view of lagoons is that they are low-energy environments, have a monotonous benthic cover of seagrass and calcareous green algae, and are the sites of mud accumulation. This description is true to a point, but is much too simplistic. Let's not be fooled into thinking that lagoons are low-energy environments. In late October 1991, a major storm in the North Atlantic generated waves which traveled south to the Bahamas. Waves were responsible for destruction of the 20-foot boat belonging to the Bahamian Field Station that was 4 feet out of the water on a boat lift. Not only the boat was destroyed, but also the lift and its cement foundation were erased from the shore. The beach was severely eroded, exposing portions of beachrock. The coastal dunes were eroded back several meters.

And let's not assume that the seagrass covers are monotonous meadows. In Graham's Harbour we commonly find areas of well-winnowed, well-sorted, abraded sands, "blowouts," and rippled sands located directly adjacent to dense seagrass communities (fig. 14) (Colby and Boardman, 1989). The benthic community (seagrass, calcareous algae,

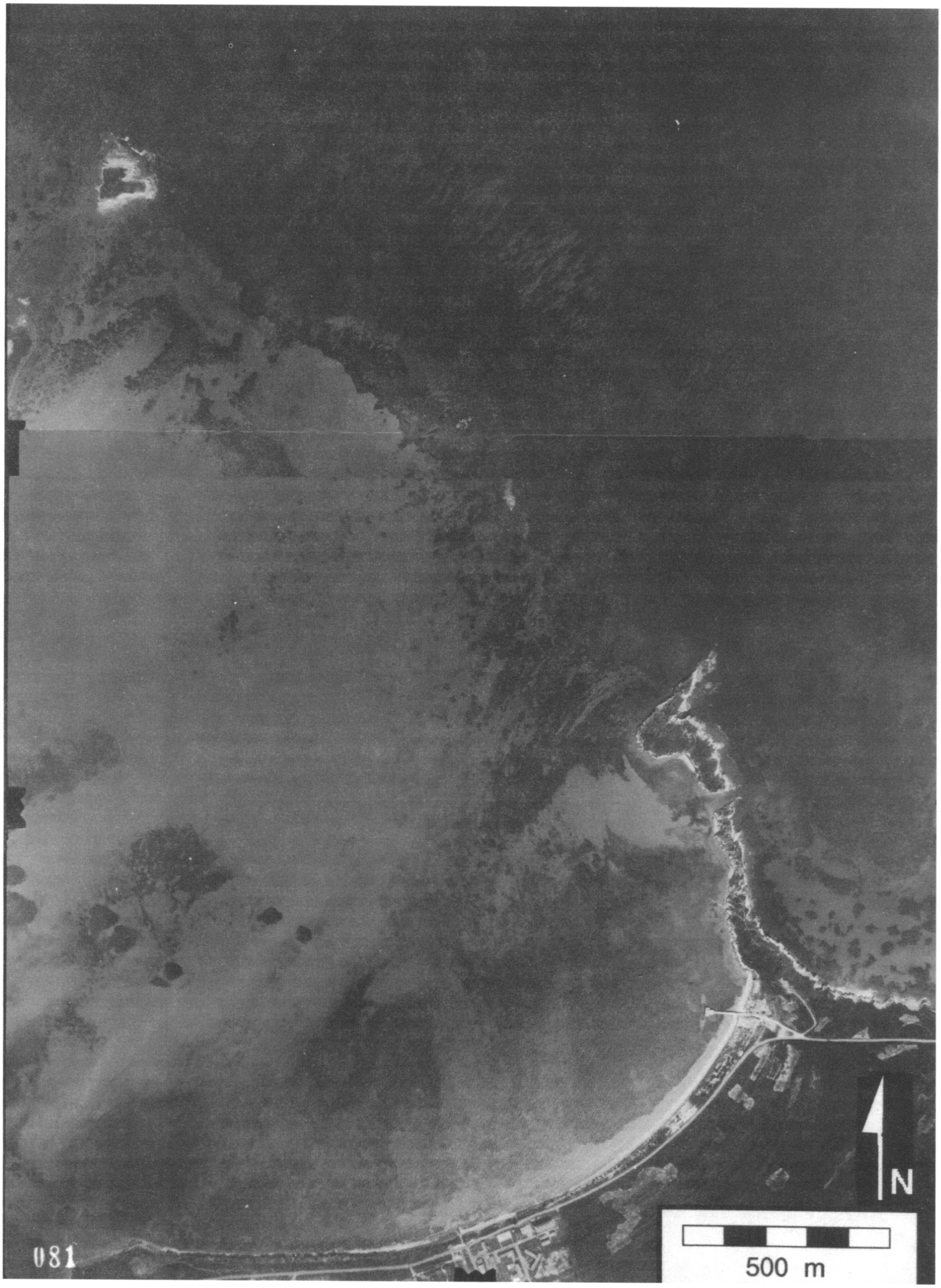


FIGURE 13.—Air photo of Graham's Harbour (1970; original scale 1:10,000).

molluscs, etc.) has a patchy distribution—patchy in terms of time and space (fig. 15).

The history of deposition of Graham's Harbour is known through extensive probing and coring (fig. 16A) (Colby and Boardman, 1989). Today, water depths attain 6 m (fig. 16B), and sediment thickness is as much as 4 m (fig. 16C). The Pleistocene "bedrock'" in Graham's Harbour is a bowl-shaped depression up to 10 m deep (fig. 16D). Fresh-water peats and/or clasts of Pleistocene bedrock are found in the bottom of many cores. C-14 dates indicate that initial marine sedimentation in Graham's Harbour began 6,000 years ago when sea level rose and flooded the platform. The

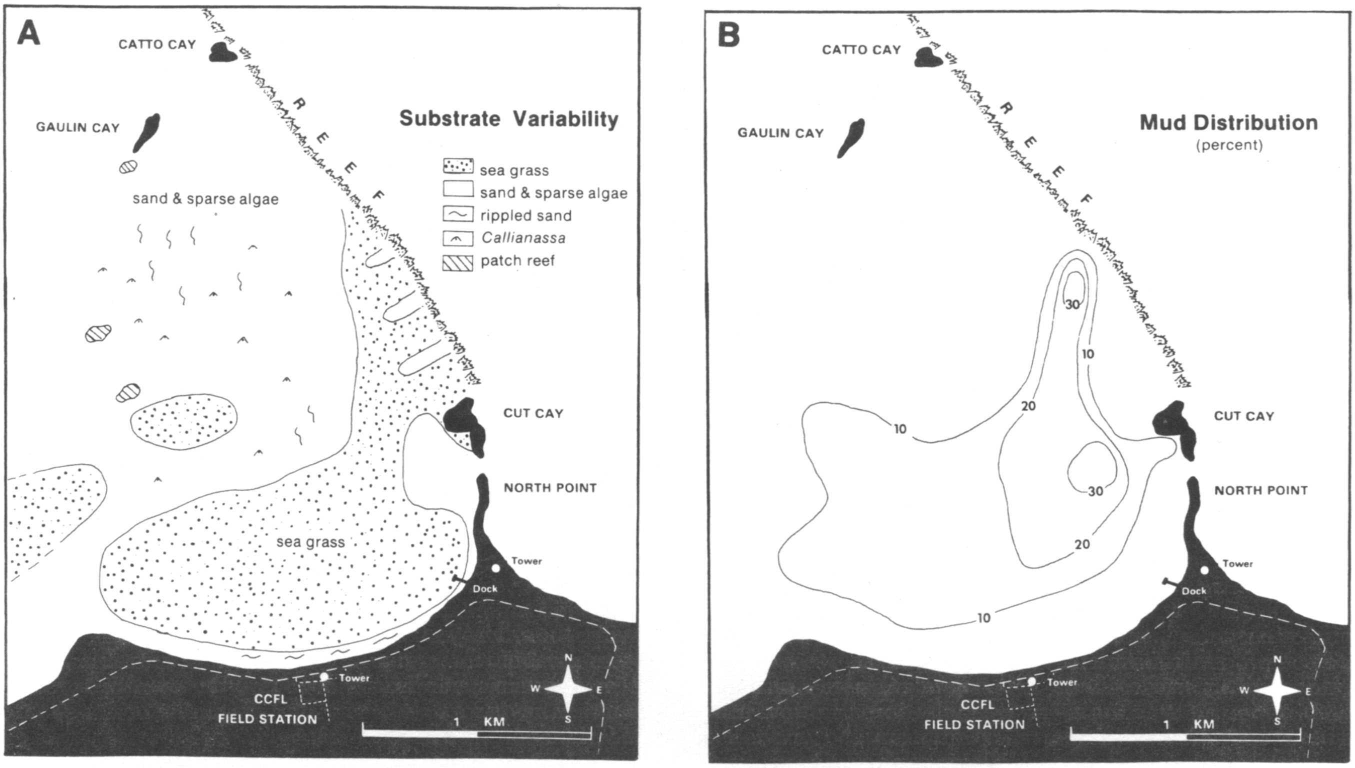


FIGURE 14.—**A**, map of benthic environments of Graham's Harbour (from Colby and Boardman, 1989). Patchiness of environments is only partly related to apparent distribution of wave energy. **B**, mud distribution in Graham's Harbour (from Colby and Boardman, 1989). A comparison of the distribution of mud at the surface and benthic communities suggests that denser seagrass causes greater mud accumulation; however, see figure 20.

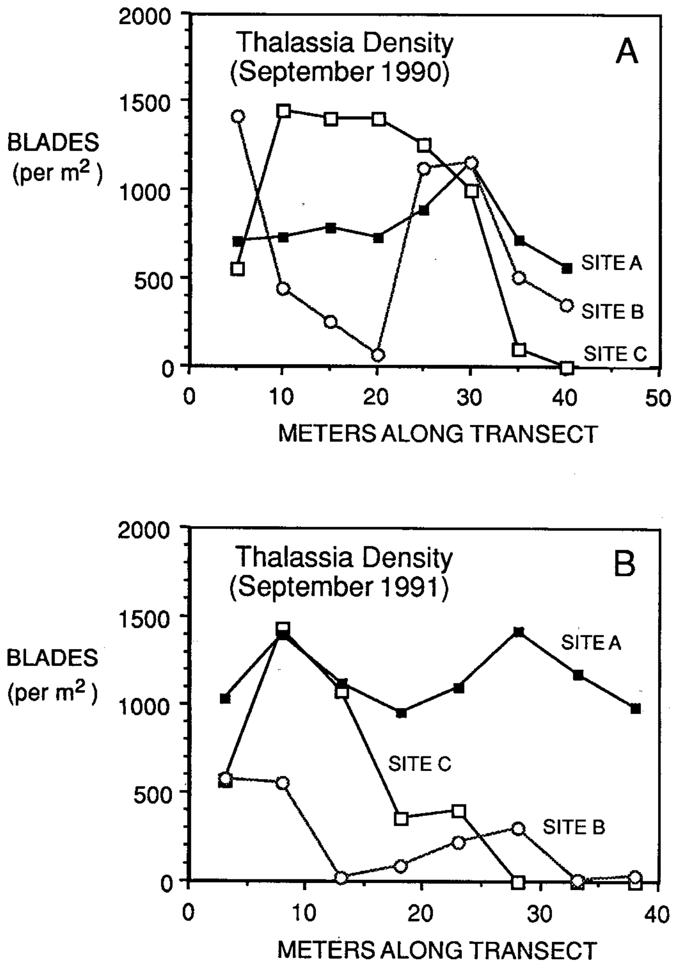


FIGURE 15.—Variability of seagrass density in time and space. **A**, census of *Thalassia* in September 1990. **B**, census of *Thalassia* in September 1991. The blades per square meter along transects in Graham's Harbour were counted by SCUBA divers.

early sediments were deposited in a quieter environment because of a pre-existing raised rim to the east and north. During the subsequent rise of sea level, the sediments became less muddy and indicate deposition in a higher energy setting (fig. 17). Throughout the history of deposition, sediment mixing has been common. Information from extensive C-14 dating of sediment fractions is interpreted to indicate that some sand (5,400 to 6,300 years old) is eroded from the dunes of North Point and added to the lagoon sand reservoir (fig. 18). Petrographic evaluation of sediment from Graham's Harbour reveals the presence of aggregates that have a similar composition to North Point rocks and which are cemented by fresh water (fig. 19) (Carney and Boardman, 1991a). Today, the lagoon is bounded to the north by a Holocene reef and to the east by North Point dunes, also Holocene.

As we swim out from the beach, you will notice that the sand is rippled. Most ripples are symmetrical and are produced by the oscillatory effects of waves. There are a few mounds and burrows of infaunal organisms (crabs, shrimp, and fish). In places, the sand is partially stabilized by a weak algal mat.

The transition from a sand-dominated benthos to a seagrass-influenced benthos is in places abrupt. Why? What controls the transition? Is seagrass prograding into the sandy area, or is the sandy area expanding at the expense of the seagrass meadow? How fast can progradation occur? Would this transition be recognized in ancient carbonates? What would we look for?

In addition to seagrass, there are various genera of calcareous green algae (*Halimeda, Penicillus, Udotea, Rhipocephalus, Acetabularia*, and *Avrainvillia*). We may see all of these or only a few. The temporal and spatial distribution of these green algae is patchy.

In places there are harder substrates (old conch shells, bottles, pieces of rock, etc.) which support a different fauna and flora. Corals, encrusting red algae, encrusting foraminifera (*Homotrema rubrum*), fish, crustaceans, sponges, and attached fleshy algae can be seen. How important are these islands of "exotic" communities to the sedimentary record of Graham's Harbour?

Notice the different types of seagrass (*Thalassia,*

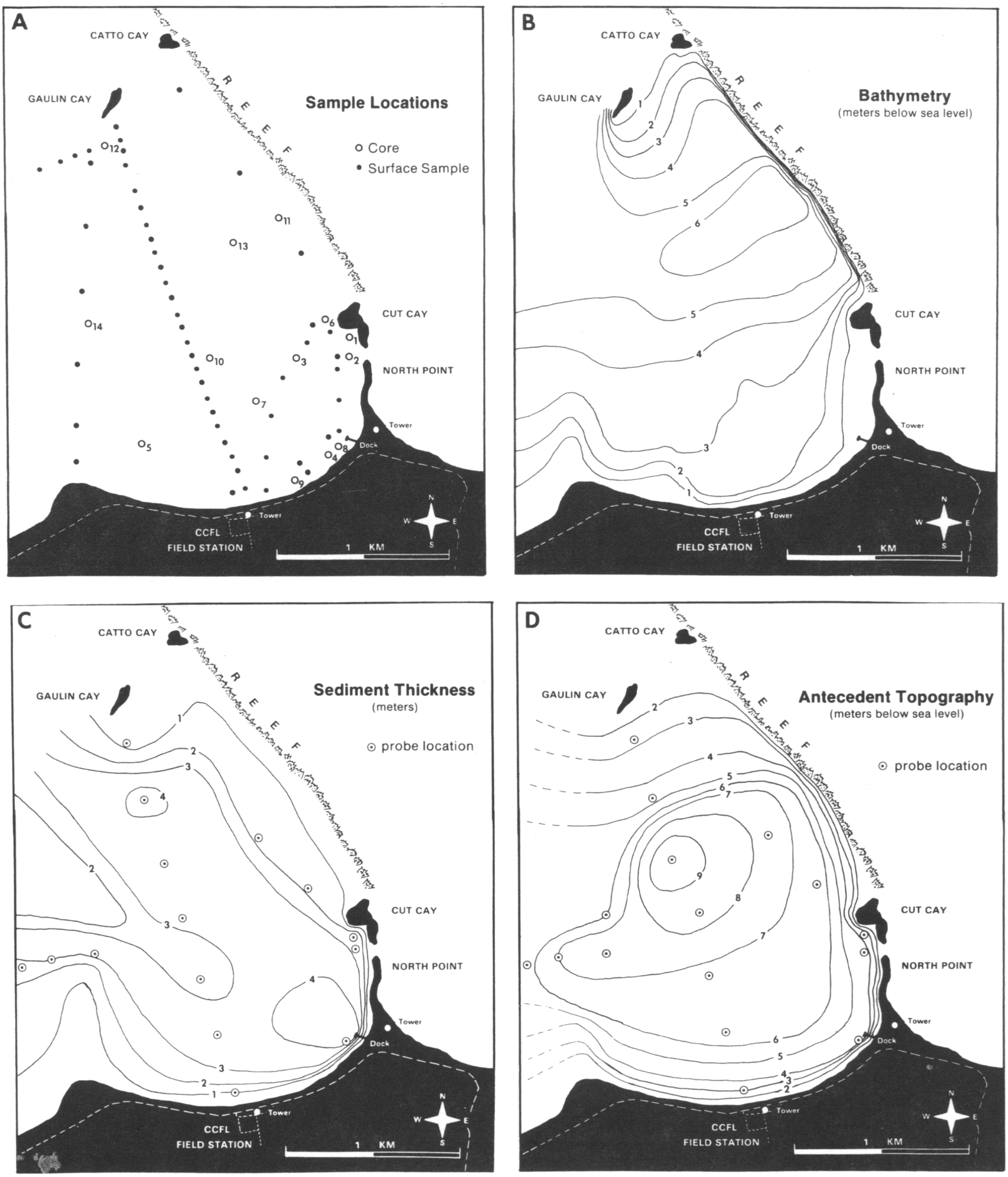


FIGURE 16.—**A**, location of surface samples, sediment cores, and probes used to determine the sequence of deposition in Graham's Harbour. **B**, water depth in Graham's Harbour; attains 6 m near the reef. **C**, sediment thickness in Graham's Harbour; generally less than 2 m and rarely more that 4 m. **D**, pre-existing Pleistocene topography in Graham's Harbour, indicating a bowl-shaped depression approximately 10 m deep prior to the rise of sea level. (From Colby and Boardman, 1989.)

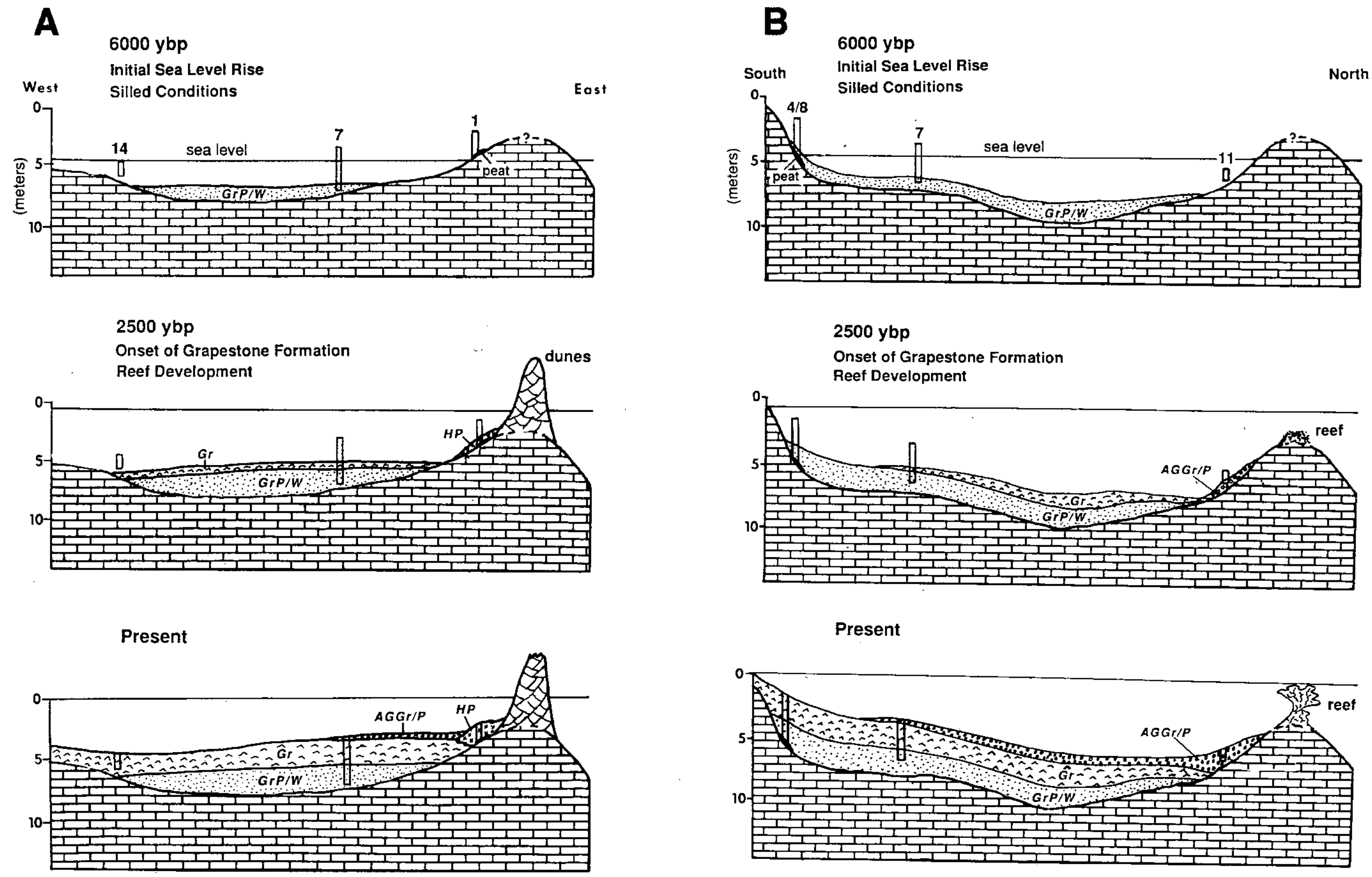


FIGURE 17.—History of deposition of Graham's Harbour (from Colby and Boardman, 1989). **A**, east-west cross section. **B**, north-south cross section. In the initial stage, sediment infilled a semi-enclosed lagoon. After sea level had risen sufficiently to "open" the lagoon to less restricted marine conditions, sedimentation became more sandy.

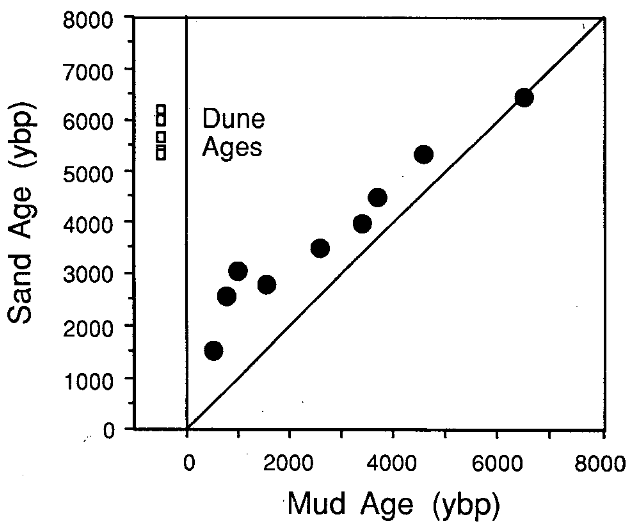


FIGURE 18.—C-14 dates of sand and mud (from Colby and Boardman, 1989). Sand dates are always older than mud dates from the same samples. The line indicates where the sand ages would equal mud ages.

Syringodium, Halodule), the density of seagrass, and the patchy distribution of seagrass. What effect will/does seagrass distribution have on physical sedimentation? What effect will types of seagrass cover have on biologic production of carbonate grains? What effect does seagrass cover have on the type and effectiveness of bioturbation (surficial and burrow)? Will any of these effects be preserved? A comparison of seagrass density and sediment texture suggests that the expected relationship of higher seagrass density generating muddier sediment is more complex than previously thought. This comparison (fig. 20) refutes the observation (fig. 14; and generally believed) that higher density seagrass is associated with higher concentrations of mud. The lack of correlation of seagrass density and percent mud in Graham's Harbour and other areas in the Bahamas and the Caribbean suggests that other factors are more important to mud accumulation than seagrass density (fig. 20) (Boardman and others, 1990).

Near the barrier reef (a couple of kilometers to the north), there are "blowouts" created during higher energy events and maintained by the higher energy normally found there.

When viewing the benthic communities in Graham's Harbour and their associated sedimentary characteristics, do we see any evidence of storms? What effect should a

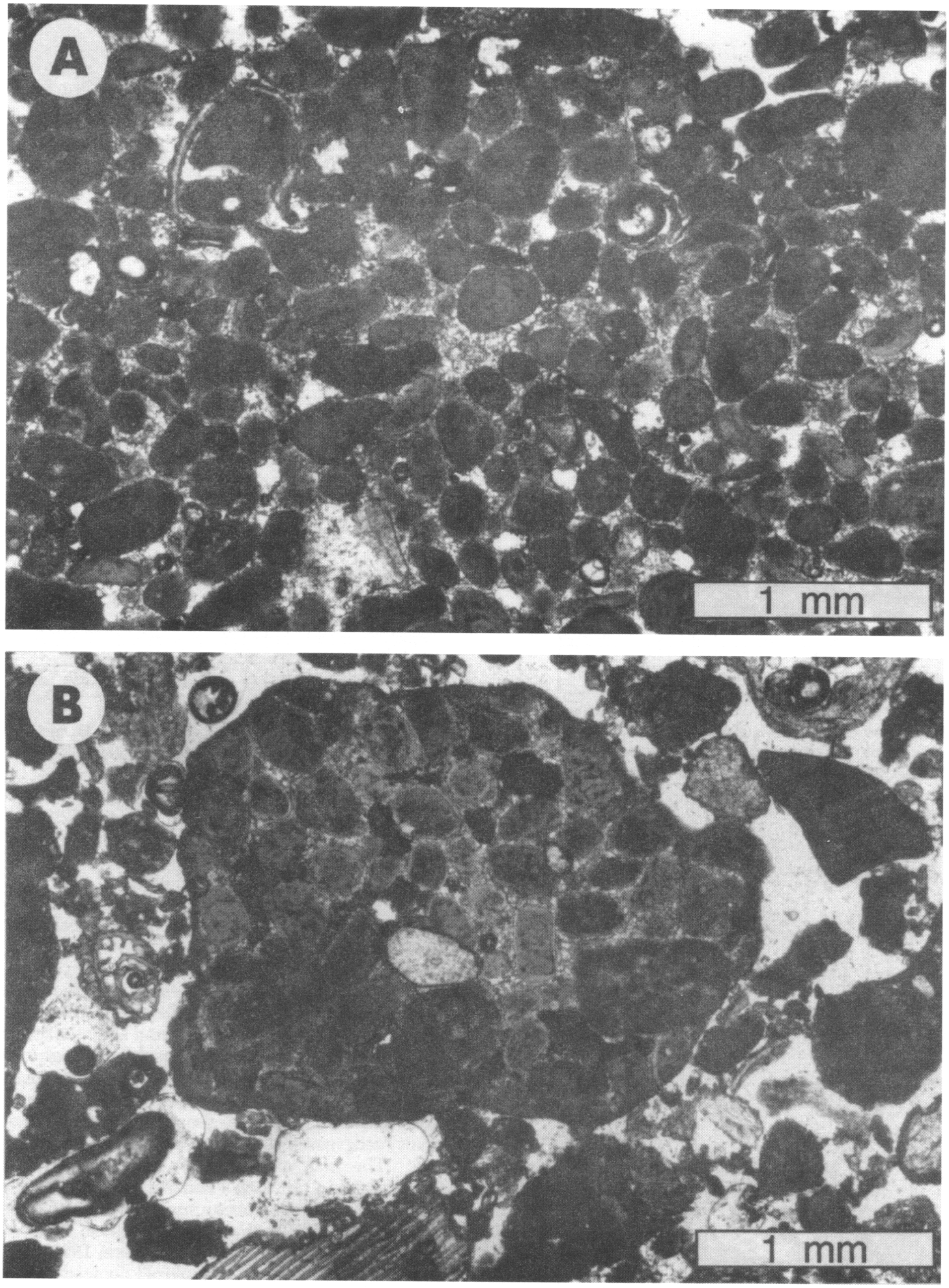


FIGURE 19.—**A**, photomicrograph of partially cemented sediment from North Point. North Point sediments contain abundant ooids and peloids which are cemented by both vadose and phreatic cements. **B**, photomicrograph of possible North Point clast in Graham's Harbour sediments.

storm have on the seagrass communities? On the sand communities? Will one storm impart an event marker bed? What would it look like in the lagoon? What would it look like in the geologic record?

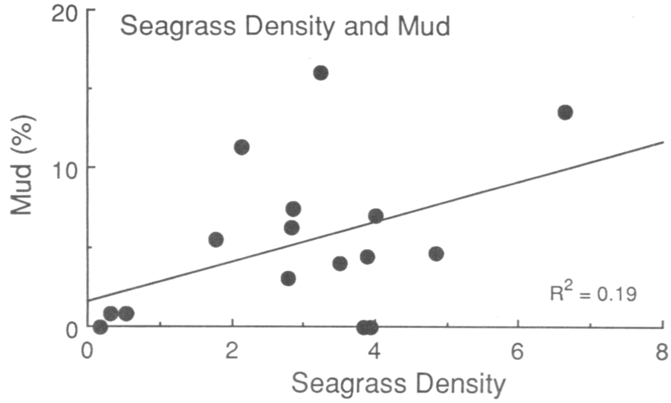


FIGURE 20.—Seagrass density verses percent mud.

IN THE FOOTSTEPS OF COLUMBUS FIELD TRIP

by
Donald T. Gerace

The final end to the remnants of medieval Europe came on October 12, 1492. On this date Christopher Columbus (fig. 21) set foot in the New World, on an island called by the indigenous people Guanahani. This event has no parallel in history, altering as it did the course of history in all nations of the world.

There are many enigmas surrounding the history of Columbus, and certainly one of the most debated is which island was the site of his first landfall in the New World. This mystery is not the result of a lack of written records, as Columbus wrote down everything he experienced during his voyage in a daily log. This log was presented to Queen Isabella after he returned to Spain, and a copy was made and given to Columbus prior to his second voyage. This copy became known as the Barcelona papers. The original log has never been seen since the death of the Queen, lost in history forever.

Fortunately, a close friend of the Columbus family, Barthlome de La Casa, a Dominican friar, made an abstract of the Barcelona copy to be used as a reference in his great work, "Historia de Las Indes." The Barcelona copy was subsequently also lost, possibly sold by Columbus' grandson, Luis, a ne'er-do-well, to support his reported excesses. Like the original holograph, it has not, to date, been found, although the copy made by La Casa was located by Martin Fernandez el Navarret in a forgotten library in 1790.

Therefore, the world has for reference of Columbus' first voyage the copy of the original holography made by La Casa and the book written by La Casa entitled "Historia de Las Indes," which has never been translated into English. Another document utilizing abstracts from the Barcelona copy is also available, written by Columbus' son Fernando and is called the "Historie." Of these documents, La Casa's copy is considered the best, as the "Historie" exists from a poor Italian translation of the missing original manuscript.

La Casa's copy of the Barcelona papers has its limitations in that it is a copy of a copy of the original log, and thus has all the ramification of such. La Casa further complained of not being able to read the scribe's writing and of having a hard time with the Admiral's Spanish, and thus he left some blanks, changed leagues to miles, and made some other obvious mistakes in transcription.

The "In the Footsteps of Columbus Field Trip" will examine what has been left in the written records from Columbus, La Casa, and Fernando, and how these relate to the geographic characteristics of the island of San Salvador. Excerpts from these documents will be *italicized* throughout this guide to distinguish them from the remainder of the text.

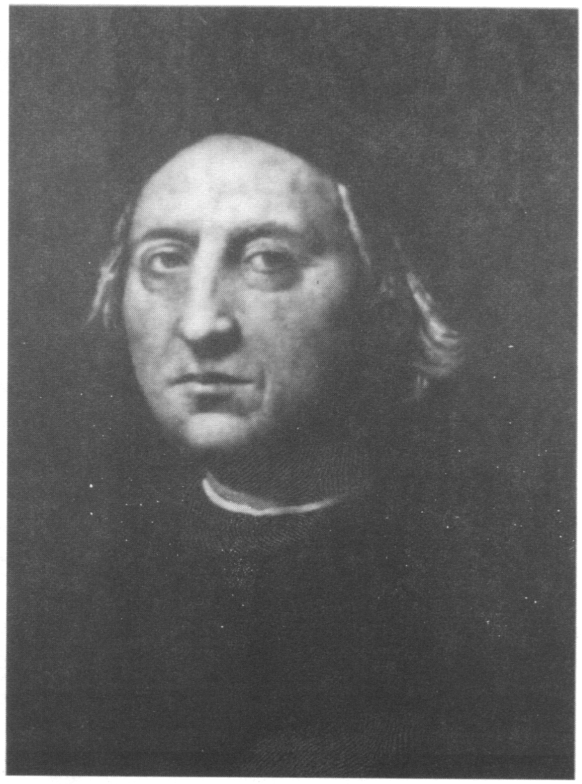


FIGURE 21.—Christopher Columbus, almost indisputably recognized by scholars as having been born in 1451. His father, Dominico, was a citizen of Genoa. Christopher had two sons, Diego and Fernando.

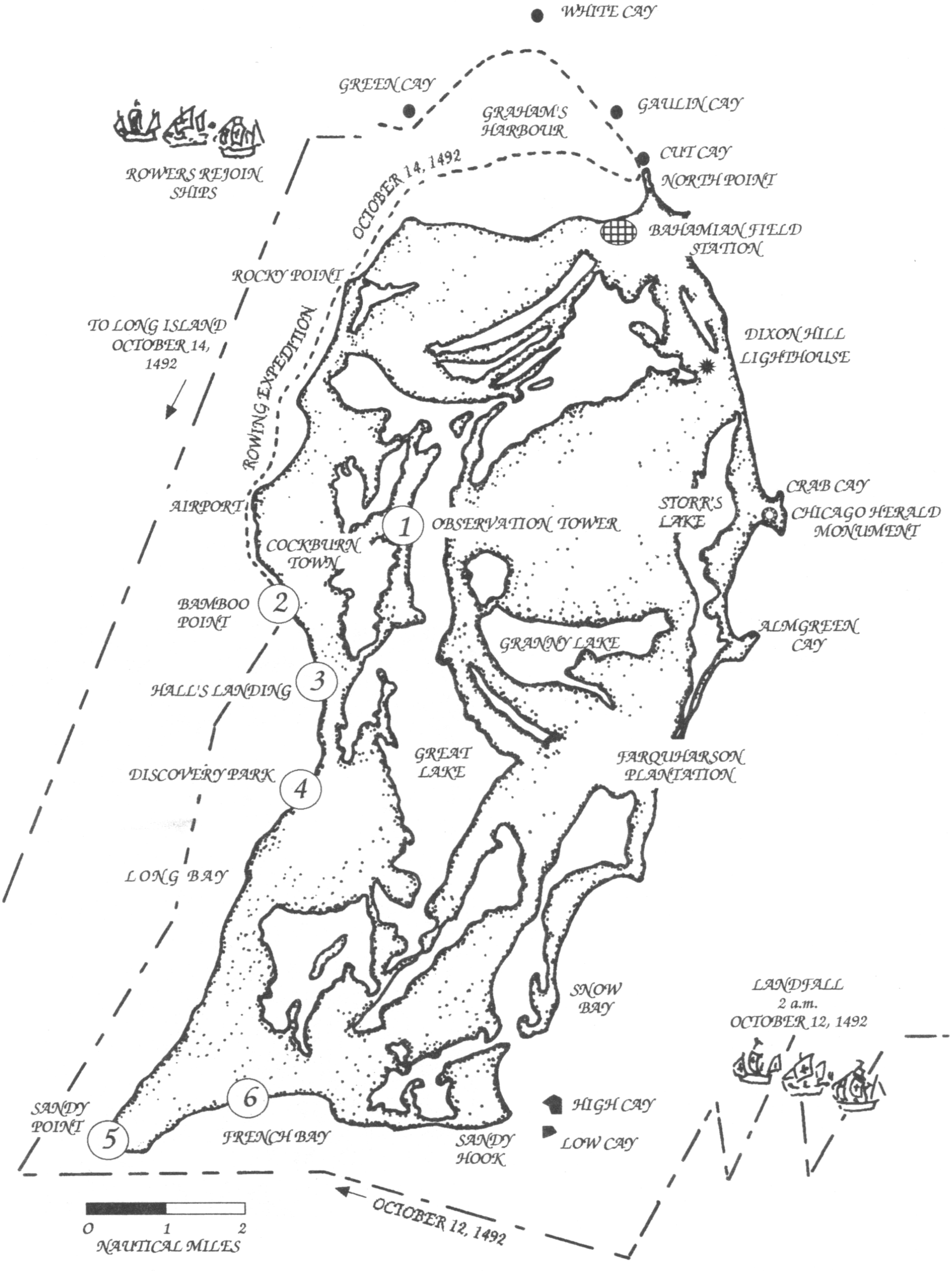


FIGURE 22.—Map of San Salvador.

STOP 1: OBSERVATION TOWER

The Observation Tower (see fig. 22 for location) provides an ideal vista of the interior of the island. Here we can see what Columbus described: *This island is quite big and very flat with very green trees and much water and a very large lake in the middle and without any mountains, and all of it is so green that it is a pleasure to look at it.*

San Salvador is the only island in the Bahamas which has such extensive inland lakes. These lakes were used for travel during the time of the Loyalist Period until the 1950's. The canal joining Little Lake and Great Lake was cut during the 19th century, allowing sailboats to travel from Cockburn Town to the Dixon Hill Lighthouse on the east side of the island, and to Farquharson's Plantation on the southeast side of the island.

These lakes have different salinities and temperatures, depending on depth and rate of evaporation. Tides flush these lakes by conduits, with direct passages to the sea or to other inland lakes. Some conduits are long enough that water exchange is not possible before tide reversal. Because the lakes have different temperatures and salinities, the specific algae which grow in each cause the various colors and opacities of the lakes.

To the northeast can be seen the Dixon Hill Lighthouse (fig. 23), erected in 1878. This is one of the last remaining hand-operated lighthouses in the world.

STOP 2: HÉLOISE MONUMENT

The Heloise Monument was erected on Bamboo Point by Paul Tappan in 1951 (figs. 22, 24). Bamboo Point is located where (1) the drop-off is closest to shore, (2) there is a break in the fringing reef, and (3) the anchorage is excellent due to a sandy bottom. Tappan, in his yacht *Heloise*, recognized this and erected the monument indicating where he felt Columbus could have made his first anchorage in the New World. This anchorage, being close to shore, would also allow the vessels to protect any landing party with their bombards and would provide an easy getaway from the shore if the natives proved unfriendly. Yachtsmen have agreed throughout history that San Salvador has only two anchorages on the west or lee side of the island, from Bamboo Point to Cockburn Town, and in Graham's Harbour.

Friday, October 12, they reached an islet of the Lucayas, which was called Guanahani in the language of the Indians. Soon they saw naked people, and the Admiral went ashore in the armed launch. Later they came swimming to the ships' launches where we were and brought us parrots and cotton thread in bulk, and we gave them, such as small glass beads and bells. They are of the color of the Canarians, neither black nor white.

STOP 3: BEACHROCK

Viewed from vehicles, beachrock (fig. 25) can be seen north of Halls Landing or at the place the field station staffers call Telephone Poles. Some beachrock is colored red by remnants of a paleosol, some black from dead algae, and others pink from the foraminiferan *Homotrema rubrum*. Columbus, on January 5, 1493, described Isla Cobra as having *rocks with many colors, good for Government buildings, like those found on the shore of San Salvador Island.*

STOP 4: WOLPER MONUMENT

The white cross at Discovery Park (fig. 26) was erected in 1954 by Mrs. Ruth Wolper, a past resident of San Salvador, as a monument to Columbus' landfall somewhere on Long Bay. Mrs. Wolper has dedicated a major part of her life to research on Columbus, his origins, his first landfall, and the Indians who met him. To this end she established the New World Museum, which houses a collection of Indian artifacts and Columbus memorabilia.

The dark areas in Long Bay are back reefs; the fore reef is nearly on the horizon. It is generally accepted by most seamen that the Admiral's fleet most likely did not land at this spot. There is no break in the fringing reef, which is located about a mile offshore, and the back-reef areas are extensive. A cumbersome vessel like the *Santa Maria* would not have been able to thread its way around such a reef to get close to shore.

STOP 5: SANDY POINT LOOKOUT

On Saturday, October 13, 1492, Columbus relaxed all day, trading with the Indians and observing these great sailors with their dugout canoes which could hold 40 to 45 men. From his inquiries of the Indians the Admiral understood that the gold he was looking for to help finance his voyage was to be found to the south and southwest.

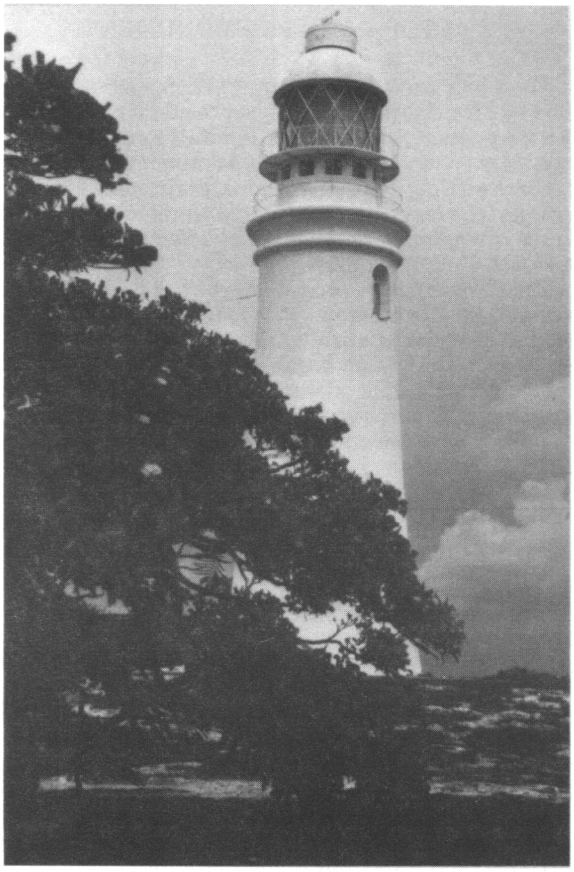
And by signs I was able to understand that, going to the south or rounding the island to the south there was there a king who had large vessels of it and had very much gold. I decided to wait until the afternoon of the morrow and then depart for the southwest for, as many of them showed me, they said there was land to the south and to the southwest and that the people from the northwest came to fight them many times.

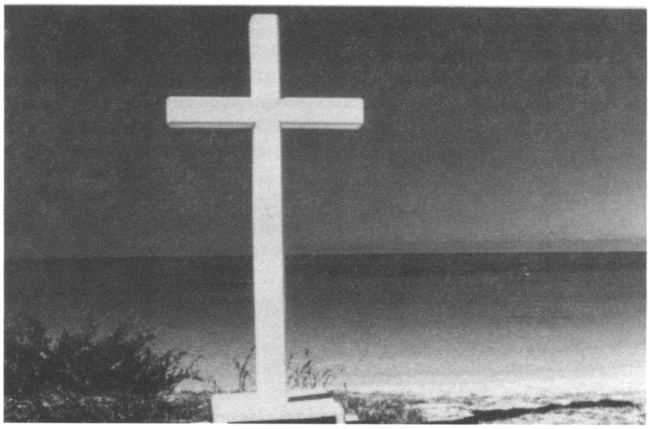
On the 14th of October Columbus departed from the northwest side of San Salvador and said *I saw so many islands that I did not know how to decide which one I would go to first.* This stop at the Sandy Point Lookout is important in that observers become aware that islands can be seen just off of San Salvador.

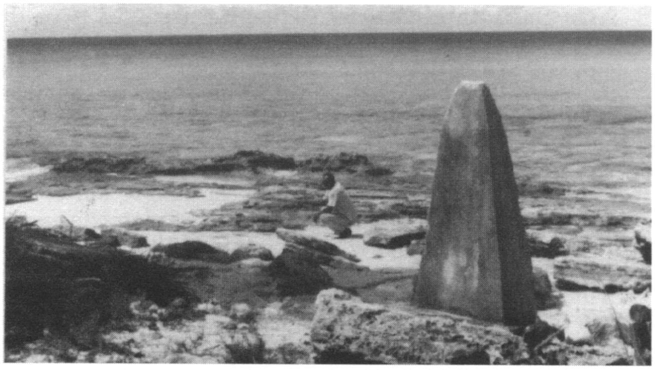
Many students, professors, and Columbus scholars have seen, under very good observation conditions, our closest island to the southwest, Rum Cay, which Columbus named Santa Maria de Conception. If the atmospheric conditions are truly exceptional, another island north of Rum Cay is visible, though rarely has it been seen from Sandy Point. This island is today called Conception and should not be confused with Columbus' name for Rum Cay.

From this point we can see French Bay with its fringing reef and the narrow channel leading into this anchorage, which is excellent during a northwestern storm. From this vista we can also see the land Columbus first saw on October 12th, High and Low Cays (fig. 27). The Admiral proceeded on the morning of the 12th around Sandy Point to get into the lee of the island. He then sailed north to the first break in the reef.

To the north of this lookout we can see the ruins of a plantation established by Loyalists who settled these British islands following the American Revolution. It is the descendants of their slaves, brought here to work cotton plantations, who make up the majority of the present Bahamian population.







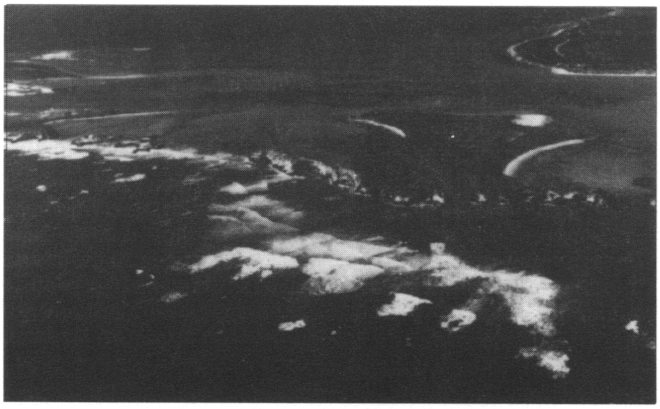


FIGURE 23 (upper left).—The Dixon Hill Lighthouse, in operation since 1878; it still uses kerosene to fuel a light reflecting from a prism, which rotates by means of hand-wound lead weights. Two lighthouse keepers, each working four hours on and four hours off, maintain this light.

FIGURE 24 (lower left).—The Heloise Monument, erected in 1951 by Paul Tappan at Bamboo Point, where the break in the fringing reef allows ships to come closest to shore.

FIGURE 25 (top right) .—Beachrock along the west coast of San Salvador such as that described by Columbus as being good for government buildings. This evaluation was probably based on Columbus' observation that the rocks break naturally into straight-sided slabs.

FIGURE 26 (middle right).—The Wolper Monument in Discovery Park. The cross is flanked by the flags of the Organization of American States.

FIGURE 27 (lower right).—High and Low Cays seen from the Atlantic side, probably Columbus' first glimpse of land in the New World. Photo taken by Virginia White.

STOP 6: BOAT TRIP

Weather permitting, and with assistance of our tender, we will depart by boat to continue our tour in the footsteps of Columbus.

Shipboard - Point of Interest 1

We have sailed from the French Bay dock to the small cays located off Sandy Hook, which were the first land sighted by Columbus in 1492 (fig. 27). Rodriguo di Triana saw the white cliffs and a sandy beach gleaming in the moonlight, according to historian Samuel Elliot Morrison. *At two hours after midnight the land appeared from where they were ahead two leagues distant. They hauled down all the sails and kept only the trio, and jogged on and off passing time until daylight.*

Columbus, however, received the 10,000 maravedes promised by the Sovereigns for the man who sighted land first. On October 11th at 10 o'clock in the evening, Columbus thought he saw a light but was uncertain, so he called Pero Gutierrez to look, and he also thought he saw it. Another seaman, Sanchez, was also asked if he saw the light, but said he did not think so. In any event, these men were poor witnesses because they both died before returning to Spain. The light, if it were on land, would have to have been seen at least 35 miles out; so we can speculate as to whether Columbus actually saw a light or was a person who could not accept anyone but himself sighting land first. Triana never got over this experience, dying in depression after reaching Spain.

We will now sail around Sandy Point to Bamboo Point. Please note the fringing reef and the distance it lies from shore.

Shipboard - Point of Interest 2

We have now come very close to shore into depths of about 14 feet of water. Imagine Columbus' fleet getting ready to anchor and claiming this new land for the Crown of Spain. How long it took the fleet to arrive here from the southeast corner of the island we do not know. However, Columbus spent the rest of the day of the 12th and all of the 13th at this anchorage.

As soon as it dawned on Sunday the 14th I ordered the ships' boats and the launches of the caravels made ready and went north-northeast along the island in order to see what there was in the other part, which was the eastern part, and also to see the villages.

This last passage tells us that the island must lie north/south and must have a face on the west side that extends northeast. It also tells us that Columbus wanted to see the eastern side of the island; so we know he must have anchored on the west side (reinforcing the fact that, being a good sailor, he would have moored on the lee side of the island, out of the trade winds). This also tells us that Columbus knew there were Indian villages along the coast.

We will now proceed along the coast, following the route of the ships' boats, to the northeast.

Shipboard - Point of Interest 3

As our boat trip proceeds we pass the Club Med site, cross Bonefish Bay, and pass Sue Point, following where Christopher Columbus rowed *to the north-northeast.* Columbus then had to come very close to the land because he described shouting to people in an Indian village. The location of this village was Rocky Point, where the reef opening makes the channel very close to shore.

I soon saw two or three villages as well as people, who all came to the beach calling to us and giving thanks to God. Some of them brought us water, other things to eat, and when they saw that I did not care to go ashore swam to us and one old man got into the boat.

Mrs. Ruth Wolper, the owner of the villa we just passed, located an Indian village site about where the young casuarina tree is located. This site was excavated by archaeologist Dr. Charles Hoffman during the 1960's.

Shipboard - Point of Interest 4

As soon as we pass Rocky Point we have a panoramic view of Graham's Harbour. No wonder the Admiral was so impressed!

They called to us in loud voices to come ashore but I was afraid, seeing a big stone reef that encircles that island all around. And in between the reef and shore there was depth and harbour for as many ships as there are in the whole of Christendom. and the entrance to it is very narrow. It is true that inside of the belt of stone there are some shallows, but the sea is no more disturbed than inside a well.

As he looked around the harbor, Columbus was afraid that he could not get out to his fleet, which probably had followed the ships' boats up the coast, but outside of the reef.

Shipboard - Point of Interest 5

Columbus was also trying to see the eastern side of the island, and a peninsula (North Point) blocked his way. He examined it and the "island which is not an island," which was Cut Cay before it was fully separated from the rest of the point. Even today the channel between Cut Cay and North Point can be crossed at low tide without getting knees wet. *I saw a piece of land formed like an island, although it was not one, on which there were six houses. This piece of land might in two days be cut off to make an island.*

Shipboard - Point of Interest 6

As we proceed past Gaulin Cay towards Green Cay we can see that along with White Cay a triangle is formed by these three small islands. This is probably why Guanahani or San Salvador was called Triangulo on some later charts.

As we approach the south side of Green Cay we can see the channel or entrance to Graham's Harbour. The harbor *has an entrance* that is *very narrow.*

Proceeding back to the Government Dock near North Point we should examine the depths, noting that the pilot must follow a channel because there are shallow depths in certain areas. *It is true that inside of the belt of stone there are some shallows.*

I looked over the whole of that harbour and afterward returned to the ship and set sail, and I saw so many islands that I did not know how to decide which one I would go to first.

Columbus does not say in his log if his ships had sailed along the coast, outside the reef, to meet him at Green Cay, or if he rowed back south to Bamboo Point. Many critics have doubted the possibility of rowing from Discovery Park to Graham's Harbour and back, a distance of 25 miles, in the time from dawn to late afternoon. A trial rowing trip was arranged in 1986 to determine the average speed of a person rowing one way from the Graham's Harbour dock to Bamboo Point. Mr. Max Ferguson started rowing at 10:51 a.m. in one

FIGURE 28.—The *Chicago Herald* Monument, at Crab Cay.

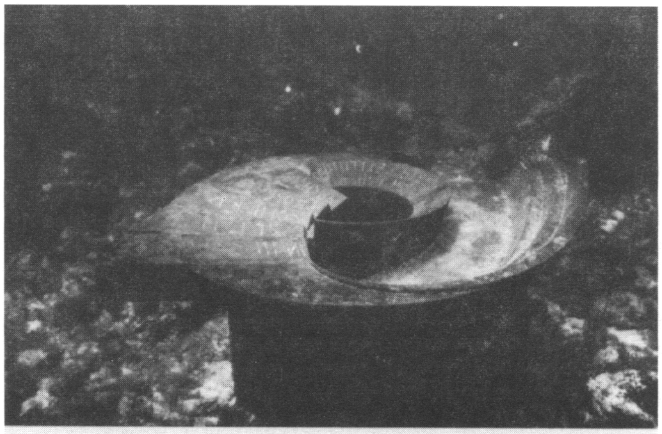


FIGURE 29.—Underwater brass plaque about 100 feet off Discovery Park, commemorating Columbus' dropping anchor in Long Bay in 1492.

of the Bahamian Field Station's wooden boats and arrived at Bamboo Point at 2:11 p.m., a distance of approximately 9 miles covered in three hours and 20 minutes. The average speed, therefore, was 2.7 miles per hour, and Mr. Ferguson looked and felt he could make a return trip to Graham's Harbour if necessary. The total distance of 25 miles would have taken a little over 9 hours, and, as described in the log, if Columbus started at 6:00 a.m., he could have made the round trip by mid-afternoon (3:30 p.m.).

OTHER MONUMENTS

If time allows, it may be of interest to visit the other monuments to Columbus on San Salvador: the *Chicago Herald* Monument at Crab Cay on the east side of the island (fig. 28) and the underwater brass plaque off Discovery Park on the west side of the island (fig. 29). The *Chicago Herald* Monument was erected at the time of the 400th anniversary of Columbus' first voyage. Prior to this time all landfall debates were by armchair historians. The *Chicago Herald* sponsored the first on-site investigation of the various islands, which resulted in San Salvador becoming the most likely choice when its geographic features were compared to those described by Columbus. The brass plaque was placed underwater about 100 feet off Discovery Park to commemorate the fact that Columbus' ships dropped anchor in Long Bay in 1492.

PIGEON CREEK AND TIDAL DELTA

Pigeon Creek is the name given to two elongate, narrow arms of a lagoon located in the southeast corner of San Salvador (figs. 30, 31). The two arms (or branches) are oriented north-south and east-west and are approximately 30 m wide and 2 km long. The arms are connected at the southeast corner where the lagoon is in contact with the more open lagoon, Snow Bay. Portions of the lagoon are shallow subtidal, and other areas are intertidal. Each branch of the lagoon contains a central channel 1 to 3 m deep and is lined by mangroves. Arms of the lagoon are not connected to a continuous source of fresh water (*i.e.*, they are not elongate estuaries). Salinity is generally highest at the enclosed ends and lowest (normal marine) at the connection with Snow Bay. Tidal fluctuations alternately fill and empty the lagoon, and tidal currents are very strong. The two branches converge at a narrow inlet, and the resulting tidal currents attain speeds of >70 cm/s (1.5 knots; fig. 32). These high currents are responsible for creating and maintaining the deep scour pits seen in the channel throat and the sandy ebb-tidal delta located seaward of the throat.

Pigeon Creek has been the site of several research projects. Teeter and Thalman (Thalman, 1983; Thalman and Teeter, 1983; Teeter and Thalman, 1984) determined from sedimentological and faunal characteristics of the northern branch that Pigeon Creek began as an open-marine environment. The area became restricted as a beach/dune ridge was built to the east. They compared Pigeon Creek to a possible Pleistocene equivalent (Quarry E, located at the northern extremity of the north-south branch of Pigeon Creek; Teeter, 1989). Mitchell (1987) described the surface sediment distribution and physical parameters of both branches. On the basis of texture and grain composition, Mitchell (1987) divided Pigeon Creek sedimentary facies into 12 groups. He agreed that Pigeon Creek is a modern analog to sediments at Quarry E except that peloids are the dominant grain type today, whereas ooids were dominant during the Pleistocene. Slone, Boardman, and Cummins (Slone, 1990; Cummins and others, 1991) examined sediment texture, density of seagrass, mollusc communities, and taphonomy of molluscs from the west branch of Pigeon Creek and compared this portion of Pigeon Creek to the ebb-tidal delta and open-ocean lagoon (Snow Bay). Their results show that, although sedimentary and taphonomic facies exist, considerable mixing of shells among environments has occurred. In addition, it is apparent that density of seagrass does not directly and dominantly control the quantity of mud accumulated or the species composition of the molluscs.

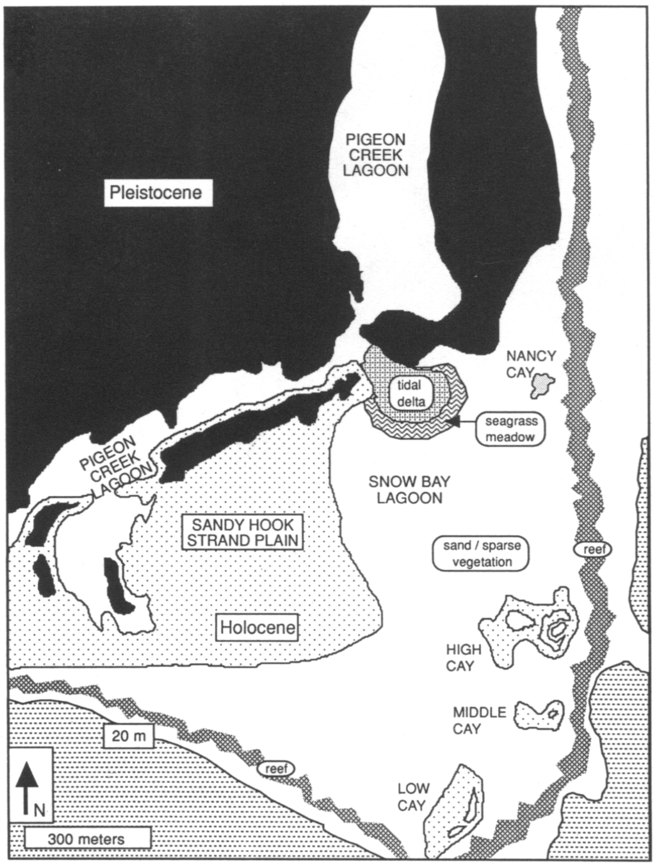


FIGURE 30.—Map of Pigeon Creek, which consists of two long, narrow branches located in the southeast corner of San Salvador. One branch is oriented north-south and the other branch is oriented roughly east-west. The boat dock, where the snorkel begins, is located at the throat of the east-west branch. Compare this map with the air photo (fig. 31) of the southeast portion of San Salvador.

PIGEON CREEK SNORKEL

We will enter the water at a public dock. The area near the dock contains a *Thalassia* meadow about 1 m deep along the channel margin, scour pits (up to 5 m deep) in the central channel, and mangroves at the edges of the lagoon. Depending on the tidal currents, when we jump in the water and begin our snorkel, we will be (1) swept up the channel towards the intertidal portions of the west branch, or (2) swept out of the throat of Pigeon Creek to the ebb-tidal delta.

Thalassia meadow

The seagrass encountered in this area is more dense than any we encountered in Graham's Harbour, yet there is surprisingly little mud (generally <5 percent). The currents (up to 70 cm/s) apparently winnow any mud that is generated here. In addition to *Thalassia*, there are areas of abundant *Halimeda*; in places, the sediment is composed of nearly 100 percent coarse *Halimeda* flakes. Abraded grains (peloids, ooids, and skeletal fragments) are also a component of the sediment.

Scour pits

The *Thalassia* meadow ends abruptly at the scour pits located in the central channel. The walls of the scour pits expose the rhizome system of the seagrass and show its powerful binding capability. Embedded on the sides of the scour pits are large molluscs in life position (prominent are a bivalve, *Codakia costata*). Chunks of the *Thalassia*-bound sediment have calved off and lie on the floor of the scour pit.

The scour pits are incredibly energetic environments, and their position within the channel is constantly changing. Covering the floor of the scour pits is a lag deposit of coarse sand and shells. Chunks of peat crop out beneath the carbonate sediment. This peat and peat layers from sediment cores in this channel have been dated (C-14) at 6,000 to 3,000 years B.P. From these dates, sedimentation rates have been estimated at approximately 100 cm/1,000 years. The scour pits are elongate parallel to the current flow, and the steepest ends are located on the western edges (up channel). Apparently the ebb current is the most active erosional force, and the scour pits are migrating up channel. On the eastern ends, the scour pits slope more gradually. During both the ebb and flood currents sand can be seen moving over the thin carpet of seagrass.

In the floor of the scour pits, notice that the shells, which seem to be dominated by *Codakia costata*, are mostly concave up. In 1990, we marked and measured 25 shells and placed them concave down in the bottom of the scour pit. One week later, we returned and located 14 of the shells. The shells had been transported up to 20 m seaward (to the east). Nearly all (13 of 14) of the shells were found concave up. No shell was found west (up channel) of the site of emplacement. Apparently, all coarse-sediment transport occurs during ebb flow.

Would a channel sequence similar to this be misinterpreted as a storm layer (sharp base, shell/sand lag, fining upward) in an ancient sequence?

In 1991, a portion of a heavily encrusted and rusting chain was found protruding from the base of a scour pit. The chain was buried under approximately 2 m of sediment. Visions of Spanish galleons, gold, jewels, and perfectly preserved artifacts rushed into our minds. Typical sedimentation rates in lagoons are in the neighborhood of 20 to

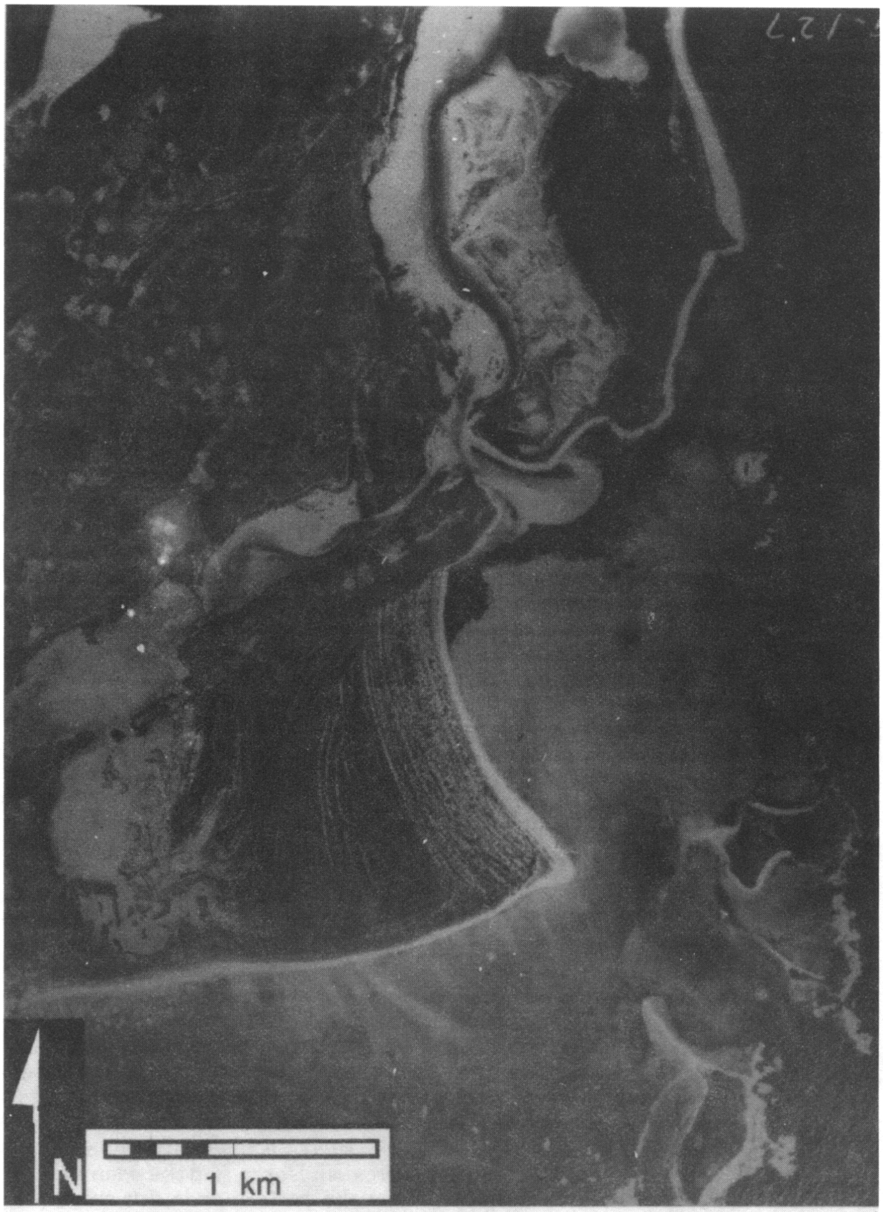


FIGURE 31.—High-altitude air photo of Pigeon Creek (1942; original scale 1:30,000) showing the locations of the main channels, intertidal areas, ebb-tidal delta, and seagrass meadows connected with Pigeon Creek. The larger, open lagoon is Snow Bay; the prograded beach ridges to the south are collectively called Sandy Hook.

60 cm/1,000 years. Sediment cores taken from this area have shown that sedimentation in Pigeon Creek is much higher, but could this chain have been buried about 500 years ago? Upon our return to the Bahamian Field Station, carefully concealed questions about the Pigeon Creek area revealed that in the past the owner of the house located about 50 m away was known to bring his 20-foot powerboat into the channel and that he had a mooring located right where the chain was found. The boat was removed, and the mooring abandoned 18 years ago! Apparently, sedimentation in this channel can be very rapid—2 m in 18 years or 11,000 cm/1,000 years! The chain mooring was located in a scour pit 18 years ago. The scour pit migrated, and the *Thalassia* meadow has prograded over the scour pit, filled it in, and is presently eroding again. What does this tell us about the rate of progradation of seagrass beds? Consider

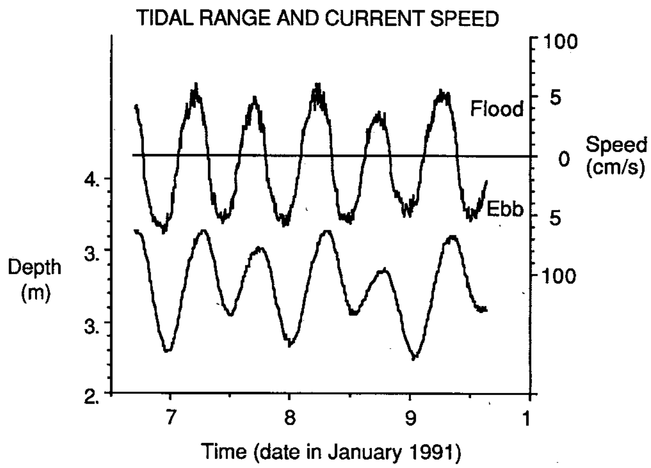


FIGURE 32.—Tidal range and current speed at the throat of the inlet connecting the western arm of Pigeon Creek with the more open lagoon of Snow Bay. The meter was emplaced in January 1991 and left for several days. Tidal fluctuation is uneven, semi-diurnal, and approximately 80 cm. Current speeds are clearly related to tidal fluctuation and attain maximum velocities of >70 cm/s. There is very little time when currents are not strong in Pigeon Creek.

how this seagrass environment compares to the seagrass environments of Graham's Harbour. Could we tell the difference between the two in an ancient sequence?

Up channel

The system of scour pits and seagrass meadows extends up the channel for several hundred meters. The channel shoals to less than 1 m water depth, the seagrass becomes less dense, and the topography of the seagrass-covered sediment becomes hummocky.

On the north side of the channel is an intertidal area of mounded sandy sediment. Sediment from a 2-m sediment core taken from this area was composed of a monotonous fine sand. Thin-section analysis of this sediment shows that the grains are dominated by peloids (48 percent), ooids (18 percent), molluscs (12 percent), aggregates (9 percent), and various other skeletal fragments.

Down channel

The scour pits grade into a deeper, sandy region located at the confluence of the two branches of Pigeon Creek. Large sand waves (1 m high) are seen on the bottom. Most of the sand waves are ebb oriented (but then we only go down the creek during the ebb tide). To the left (north) the northern branch of Pigeon Creek can be seen.

Tidal delta

As we continue down the channel and out the mouth, a sandy tidal delta (ebb-tidal delta) is encountered. The surface geometry of the delta is concave up. An intertidal portion is located in the center, and deeper areas lie around it. The outer margin of the delta is marked by an abrupt transition to seagrass. In places the seagrass/sand margin is an escarpment in which the seagrass rhizome system is exposed, and the sand is up to 50 cm deeper than the seagrass. This suggests that the seagrass has eroded. In other areas, there is no difference in topography, the seagrass density gradually changes over a distance of several meters, and it is not clear whether the sand delta is prograding over the seagrass or the seagrass meadow is prograding over the delta. How fast is this progradation occurring? When did it start? The history of this progradation is estimated from four sources of information.

(1) In 1986, we embedded PVC and aluminum tubing at the seagrass/sand boundary, in the seagrass 1 m from the sand edge. These tubes were placed every 10 m. As you snorkel around the edge of the delta, tubes may be encountered stuck in the sediment. In the sand areas, the tubes will be recognized because they are covered with tufts of algae, and fish may have made a home of the tube. Some tubes are located up to 10 m from the edge of the delta, indicating that, in that area, the delta has prograded 10 m in the last few years. In other areas the tubes are still in the seagrass, 1 m from the edge of the sand, indicating no movement of the sand/grass boundary. In no place have we found that the seagrass meadow has prograded over the sand delta.

(2) Sediment cores taken from the seagrass meadow near the edge of the delta contains muddy sand with abundant whole molluscs and other skeletal material. Sediment cores from the delta reveal a meter or so of abraded, well-sorted sand underlain by a muddy sand with abundant whole molluscs and other skeletal material. These sequences confirm that the delta is prograding over the seagrass meadow.

(3) C-14 dates of the sand in the delta indicate that the sand is approximately 2,000 years old. However, C-14 dates from the mud fraction of the sediment immediately beneath the delta sand are much younger than the overlying sand (a C-14 date inversion). In a core from the central portion of the delta, at the boundary between muddy sand (seagrass sediment) and delta sand (60 cm deep in the core), the underlying mud is 600 years old, whereas the overlying sand is 2,560 years old, indicating that the delta has indeed enlarged significantly during the last 600 years. The delta sand is anomalously old because it is a mixture of early Holocene sand and modern sand.

(4) When Dr. Don Gerace, the director of the Bahamian Field Station, first came to San Salvador, he piloted a 55-foot ketch across the delta and into Pigeon Creek. He went up the creek, anchored, turned around, and left. Today, that would not be possible. He reports that the entry to the channelway and the channel itself have certainly changed.

It is also interesting to note that, at the confluence of the two branches of Pigeon Creek, there are remains of an Indian village. It is thought that the Indians would probably not have located in an area where access to the sea would be restricted.

Based on these various sources of information, it seems evident that the delta is a geologically recent and dynamic feature. What caused it to form? What is its genetic relationship to Pigeon Creek, to the Sandy Hook strand plain, to the relict offshore sand dunes (*e.g.*, High Cay), and to the upward growth of reefs?

FIGURE 33.—High-altitude air photo (1970; original scale 1:10,000) in which the low, arcuate beach ridges of Sandy Hook are clearly visible because of differences in vegetation between the crests and troughs of the ridges. Several different orientations of ridges are present and probably represent different intervals of deposition and erosion caused by varying wave climate.

SANDY HOOK STRAND PLAIN

Sandy Hook is a Holocene strand plain (1.5 by 1.5 km) located on the southeastern margin of San Salvador (see fig. 30). The strand plain system consists of beach/dune ridges (approximately 35) which have prograded to the east and which are arranged in several packages with distinct orientations (fig. 33). Sandy Hook is bounded by a Pleistocene ridge to the north, Pigeon Creek to the west, and shallow lagoons to the east and south.

The composition and structure of the Sandy Hook strand plain was investigated using a number of techniques. A modified rotary drill was used to extract cores of the unconsolidated and partially consolidated sediments at four sites on the strand plain to a depth of 2.5 m. Two pits were dug to examine sedimentary structures and insure in-place sampling (fig. 34). Two zones of partially cemented sediments were encountered at sites B, C, and D. These cemented zones are bedded, range in thickness from 20 to 50 cm, have a sharp lower boundary and a gradational upper boundary, and dip seaward at angles similar to present-day beaches. Sediments are composed of peloids, rounded and abraded skeletal grains, ooids, and aggregates (figs. 35 and 36A). The grain-contact and rim cements are patchily distributed and are composed of blocky low-Mg calcite.

A ground-penetrating-radar (GPR) survey of Sandy Hook (see fig. 34) revealed a series of strong reflectors dipping seaward on transects perpendicular to the shoreline (fig. 37A) and horizontal reflectors on transects parallel to the shoreline (fig. 37B). These reflectors have the same orientations, dip angles, and depths as the cemented layers. One possible explanation under investigation for these reflectors is that they are slabs of buried beachrock (Stoyka, 1992; Stoyka and others, 1992). A beachrock origin would satisfactorily account for the GPR results, but the blocky calcite cement present in the cemented zones is not what is typically expected for beachrock cements.

Beachrock forms in the intertidal zone (fig. 38) and is typically cemented by a fringe of fibrous aragonite or micritic high-Mg calcite (Bathurst, 1975). Beachrock cements are thought to form under a thin cover of sediment and to originate from processes active in the intertidal (beach) zone (*e.g.*, evaporation of seawater, CO_2 degassing of fresh meteoric waters, mixing of fresh water and seawater). The blocky calcite cements of Sandy Hook are more typical of fresh-water, meteoric cements. However, cements with this mineralogy and morphology can be present in the upper intertidal zone of beaches (Illing, 1954; Bathurst, 1975; Bain, 1989). Samples of beachrock were obtained along transects at two localities on San Salvador (Graham's Harbour and Bonefish Bay) for comparison with the cemented zones of Sandy Hook. Petrologic examination revealed that sediments lowest on the beach were cemented by fibrous aragonite (fig. 39), and those highest on the beach were cemented by blocky calcite (fig. 36B). From this evidence, a beachrock interpretation for the cemented zones at Sandy Hook cannot be ruled out. It is also possible that sediments deposited as a beach were later exposed to meteoric conditions and cemented as the beach system prograded seaward. The top of the fresh-water lens is presently near the level of these layers (*i.e.*, at sea level), and cementation may be continuing today.

As we drive along the Pleistocene ridge, the various carbonate sand environments of the Sandy Hook area can be seen. Eastward of the strand plain are a sandy lagoon (Snow Bay) and eolian Holocene dunes (High Cay, Nancy Cay, Hinchinbroke Cays). A petrologic comparison of sedi-

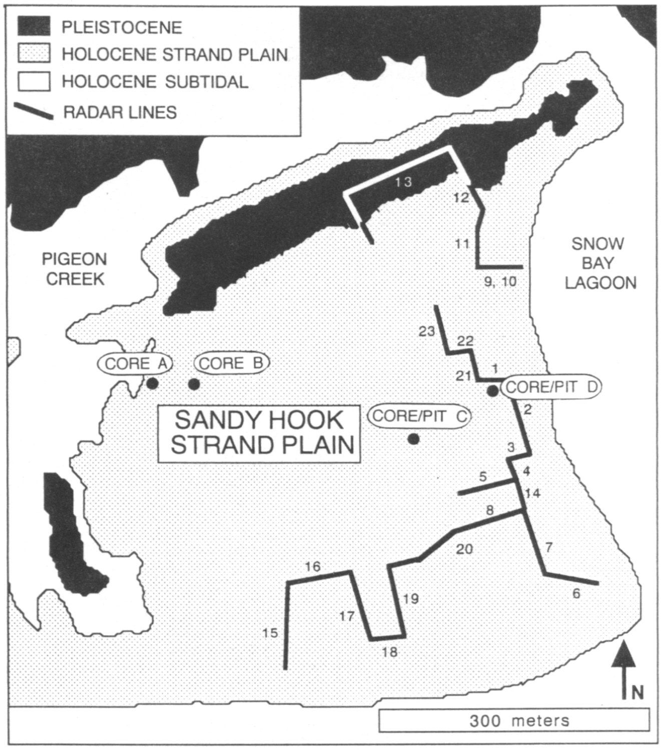


FIGURE 34.—Four sites on Sandy Hook sampled by pits and cores. Ground-penetrating radar lines are oriented parallel and perpendicular to the orientation of the ridges. Compare the orientation of radar lines to the air photo of figure 33. Radar traces of lines 3 and 4 are shown in figure 37.

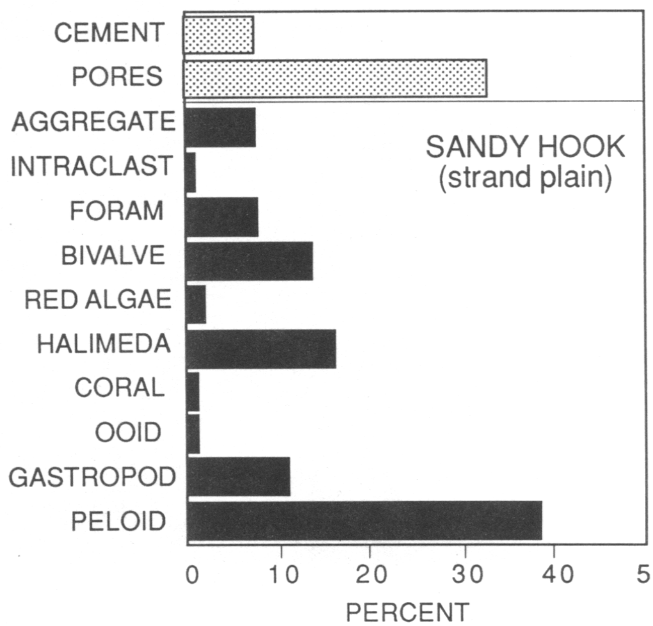


FIGURE 35.—Results of petrographic examination of samples from Sandy Hook; peloids and skeletal material are abundant. In this figure, the total percentage of grains adds up to 100%; the percentage of cement and pores are percent of the whole sample.

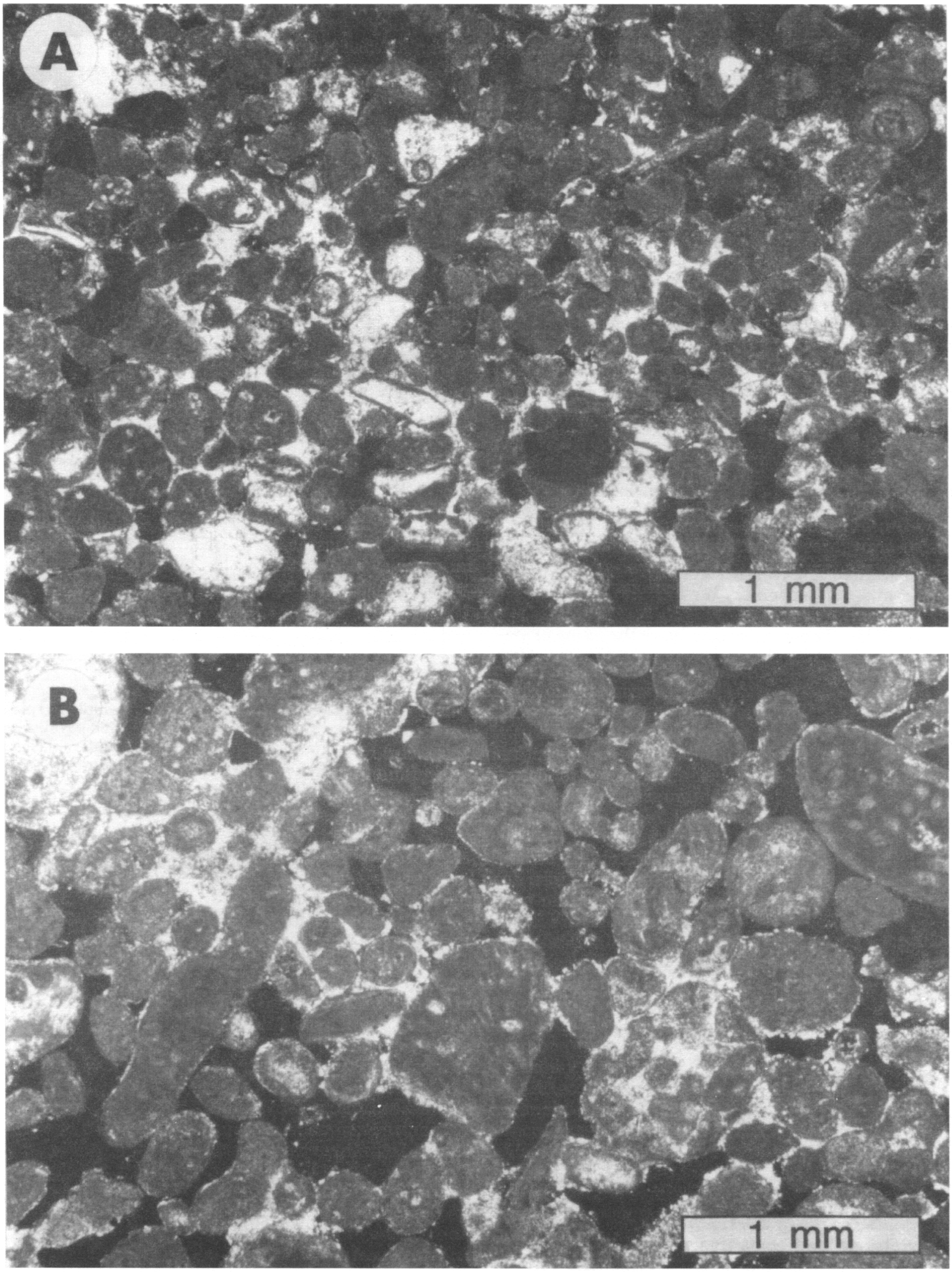


FIGURE 36.—**A**, photomicrograph of partially cemented zone in Sandy Hook sediments. Blocky, low-Mg calcite is abundant at grain contacts and also is present as rim cements. **B**, photomicrograph of beachrock with blocky fresh-water cements like those from Sandy Hook cemented zones; from upper portion of beachrock at Bonefish Bay near the Old World Museum.

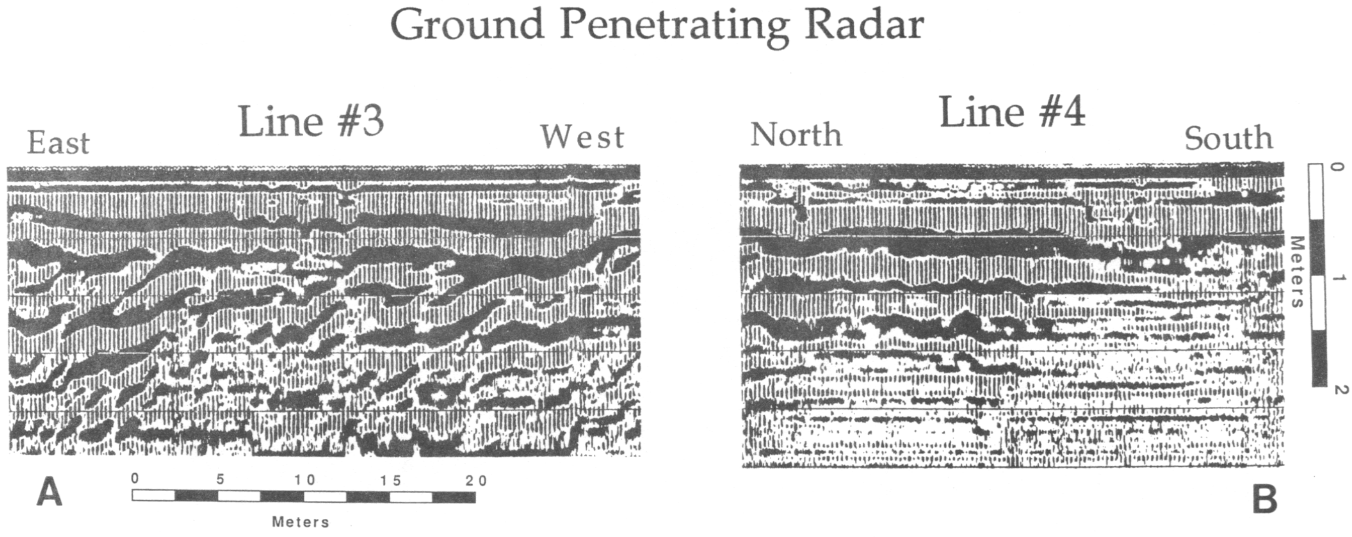


FIGURE 37.—**A**, ground-penetrating-radar trace from transect 3, taken perpendicular to the shoreline and showing reflectors dipping seaward. **B**, ground-penetrating-radar trace from transect 4, taken parallel to the shoreline and containing only flat reflectors. See figure 34 for locations of transects.

FIGURE 38.—Slabs of beachrock dipping seaward into Bonefish Bay. The dip angle of the beachrock is similar to the dip angle of the ground-penetrating-radar reflectors (see fig. 37). Portions of the beachrock are nearly always bathed in marine water; the upper portion of the slabs are commonly exposed to meteoric waters. This difference may explain the difference in cementation (figs. 36B and 39).

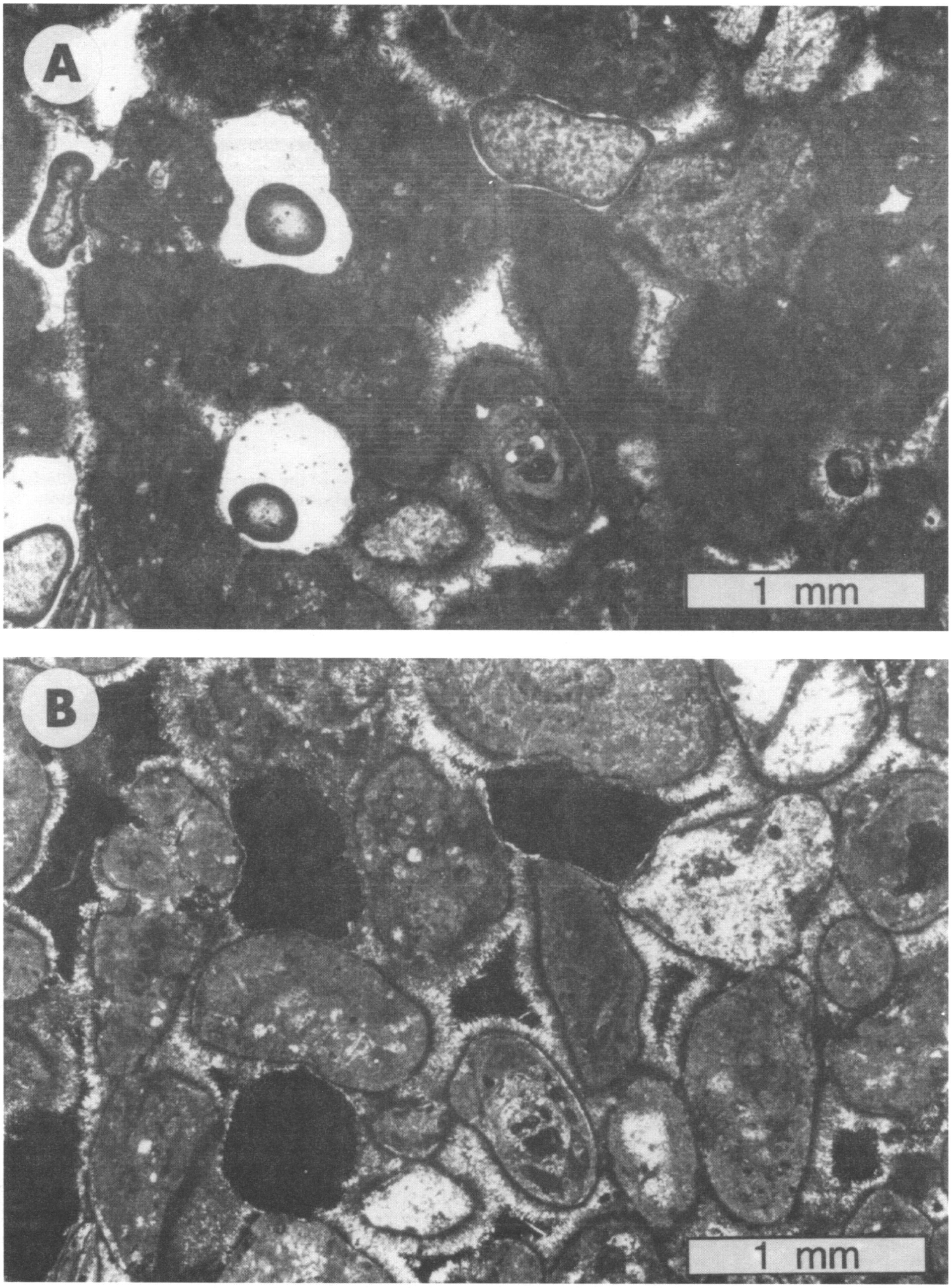


FIGURE 39.—Photomicrograph of typical beachrock with fibrous aragonite cement; from lower portion of beachrock at Bonefish Bay. **A**, plane-polarized light. **B**, crossed nicols.

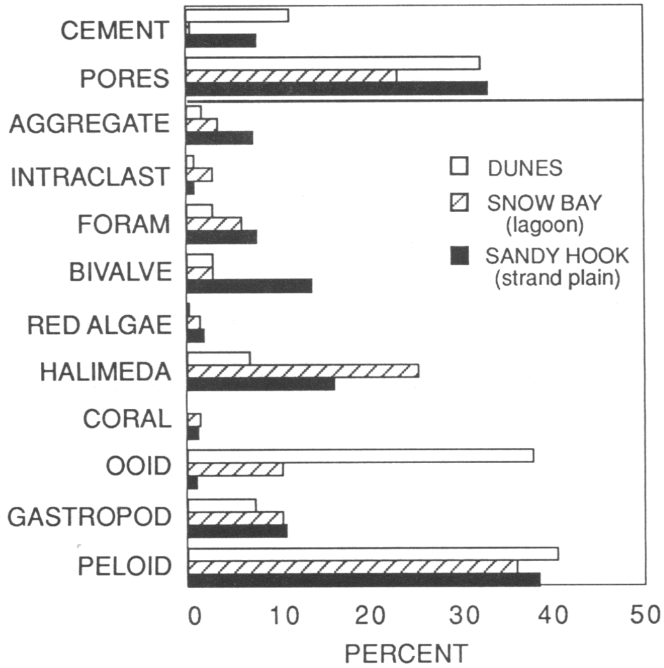


FIGURE 40.—Grain composition of sand units in southeastern San Salvador. The sediments are dominated by peloids, and there are only slight differences in grain composition. Ooids are abundant only in the Holocene dunes (*e.g.*, High Cay, Nancy Cay). As expected, *Halimeda* is most abundant in the lagoonal samples of Snow Bay. In this figure, the total percentage of grains adds up to 100%; the percentage of cement and pores are percent of the whole sample.

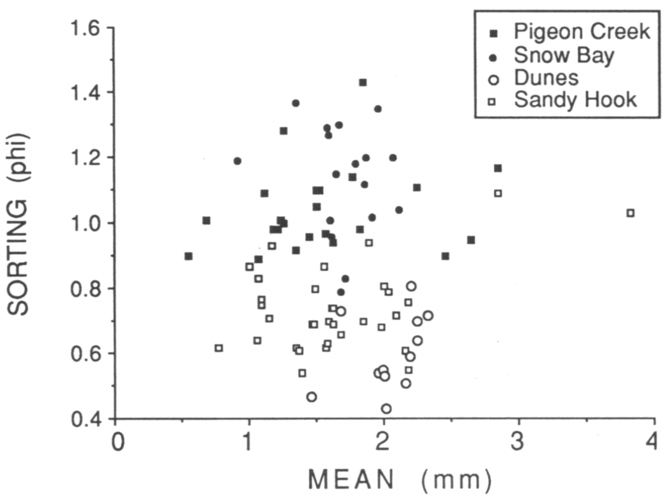


FIGURE 41.—Mean grain size and sorting of samples from southeastern San Salvador. They segregate themselves into a subtidal group shown by solid squares (Pigeon Creek lagoon) and solid circles (Snow Bay lagoon) and a supratidal group shown by open circles (Holocene dunes) and open squares (Sandy Hook strand plain). The supratidal sediments are generally better sorted than the subtidal sediments.

ments and rocks from Snow Bay, Sandy Hook, and the Holocene dunes shows that there are only subtle differences in grain composition among these environments of deposition (fig. 40). Even though mean grain size and sorting values (fig. 41) can be used to distinguish subtidal (Pigeon Creek, Snow Bay) from supratidal (Holocene dunes and surficial strand plain) sediments, it is likely that if these sediments were preserved, they would be interpreted as one large undifferentiated carbonate sand body (Boardman and others, 1991; Kim, 1991).

The early Holocene dunes have a high percentage of ooids (approximately 40 percent of total grains; fig. 40). In both the subtidal and strand plain sediments an upward-decreasing concentration of ooids is seen (fig. 42). In addition, oolitic clasts cemented by fresh-water cements are present in sediments from Snow Bay and Sandy Hook. Apparently an ooid-generating period occurred early in the Holocene and created dunes (*e.g.*, High Cay which is composed of oolitic sediment cemented by fresh-water cement); clasts of dune material found in subtidal and strand-plain sediments indicate that transport and mixing has occurred among the environments.

A model for the depositional history for this area and its

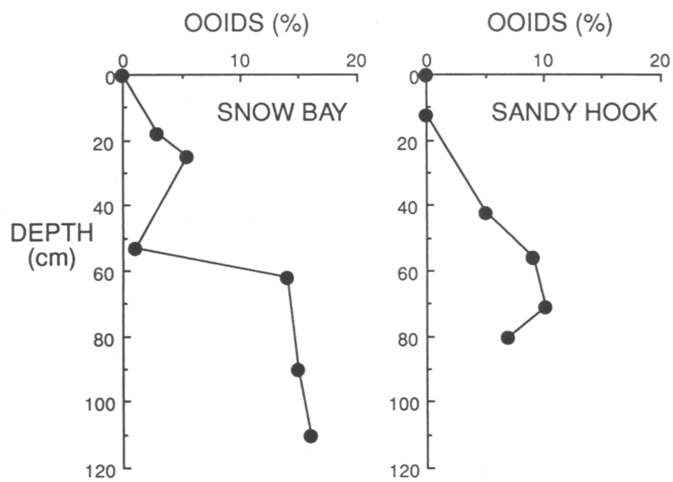


FIGURE 42.—Percent ooids vs. depth in cores of the upper portion of Sandy Hook and Snow Bay sediments; there is a slight increase in the proportion of ooids with core depth.

relation to the Holocene rise of sea level is shown in figures 43 and 44. Approximately 6,000 years ago, oolitic deposits were formed as the sea trangressed over the shelf. Ooids and bioclastic grains were blown up into high eolian dunes located offshore from Sandy Hook such as High Cay and Nancy Cay. As sea level continued to rise, the area behind the dunes was flooded forming a lagoon (Snow Bay) and coastal beaches (earliest Sandy Hook beaches). The formation of the lagoon created a skeletal-producing environment. Erosion of the high dunes began, mixing ooids and oolitic clasts into lagoonal (skeletal) sediments. As the rate of sea-level rise slowed 3,000 years ago, the Sandy Hook strand-plain system began to prograde. This progradation has resulted in the formation of the series of beach/dune ridges that are observed today.

We will stop briefly at the Gazebo at the southernmost point of Sandy Hook. Here we can see the modern beach and portions of the modern strand plain (partially cemented) that is prograding seaward.

The southwest portion of San Salvador is highlighted by

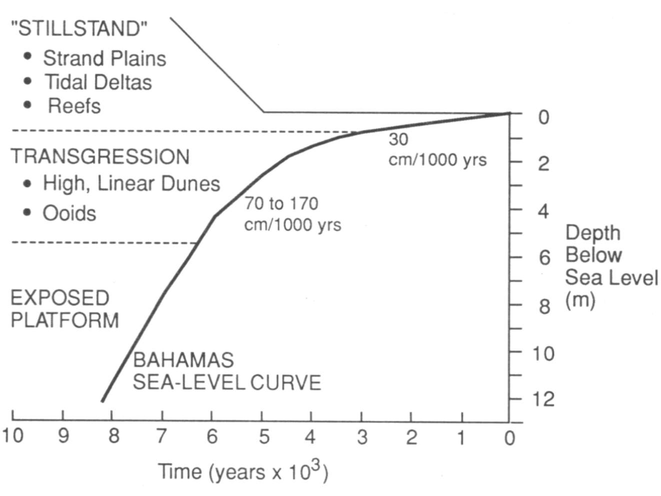


FIGURE 43.—Sea-level curve for the Bahamas (after Boardman and others, 1989) showing relative changes in rate of sea-level rise through time and sequence of development for southeastern San Salvador.

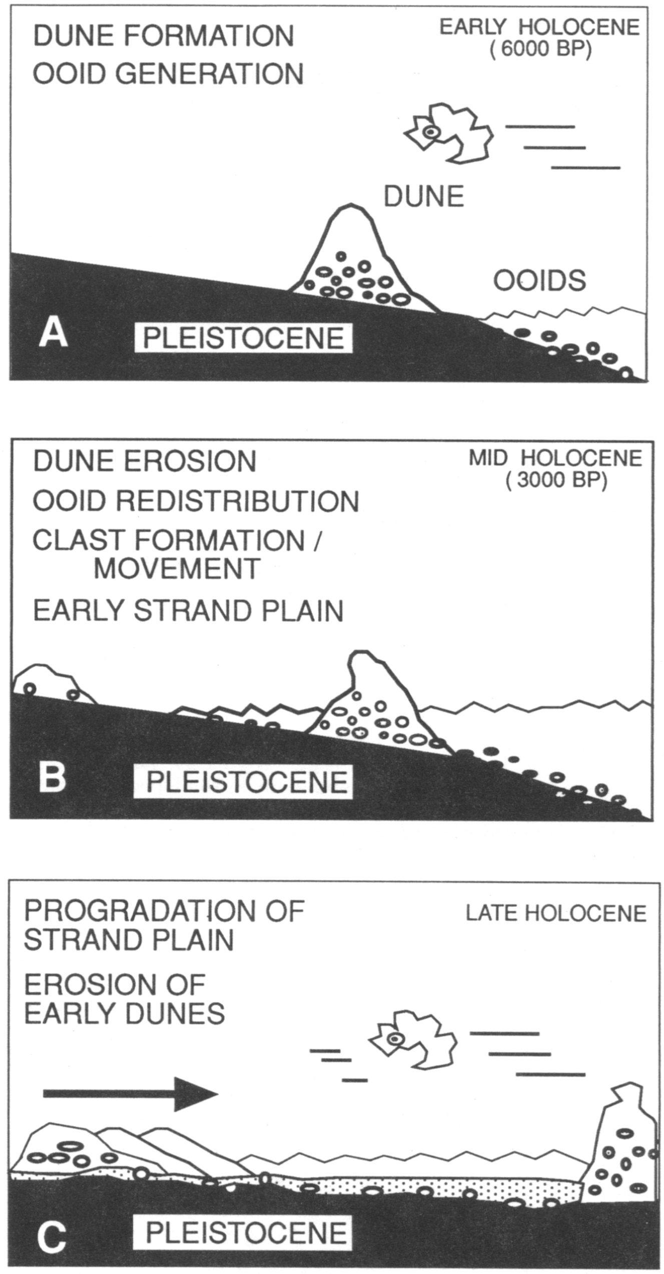


FIGURE 44.—The evolution of Sandy Hook is linked to the origin, growth, and decay of the early Holocene dunes and Snow Bay lagoon. **A**, an early Holocene episode of ooid generation and dune formation was followed by **B**, "drowning" of the dune and jumping of the shoreline to a position farther inland. Erosion of the early-formed dunes contributed an ooid-rich sediment to the lagoon and newly formed beach ridge. **C**, as the rate of sea level slowed, beach ridges were stranded as the shoreline prograded. Earlier formed sediment from the lagoon and from the early Holocene dunes were mixed with contemporary sandy sediments.

GROTTO BEACH

an accumulation of Holocene sand in the form of a strand plain which includes one of the highest energy beaches—Sandy Point—as well as one of the most beautiful beaches on San Salvador—Grotto Beach (see fig. 7). Grotto Beach gets its name from the presence of small "caves" (grottos) along the rock face to the north of the beach.

THE MODERN BEACH

As we first enter the beach area, pick up some sand and examine it. Look at the texture and compare it to the sand we have seen in Graham's Harbour, Pigeon Creek, the ebb-tidal delta at Snow Bay, and the strand plain of Sandy Hook. The sphericity, rounding, polish, and sorting of Grotto Beach sand grains are most similar to the ebb-tidal delta sands. However, the Grotto Beach sands are somewhat coarser than any of the sands we have seen thus far (except for the "sand" in the Pigeon Creek channel scour pits). This coarse texture suggests that Grotto Beach is a high-energy beach. In addition to the texture of the Grotto Beach sand deposit, the high angle of the beachface indicates a high-energy beach. Depending on recent storm activity, an erosional scarp may be present. There is an apparent geologic contradiction in that Grotto Beach and Sandy Point are located on the leeward margin (*i.e.*, protected), and a prograded strand plain and features indicative of a high-energy coast are not what are expected.

There are several possible reasons for the high-energy conditions found here, and a comparison of Grotto Beach with the beaches at Sandy Hook (not to be confused with Sandy Point) illustrates some of the processes controlling shoreline characteristics. Sandy Hook is located on the east side of San Salvador and faces the prevailing trade winds. Theoretically, it should have higher energy beaches. However, there is a barrier to high wave energy in the form of offshore islands, reefs, and a shallow lagoon. The energy of waves, created at sea in storms many kilometers away, is dissipated by the remnants of the early Holocene dunes and the reefs which have grown during the most recent relative stillstand of sea level. In addition, pre-existing topography (Pleistocene) puts the eastern shoreline farther from the platform margin, and today a broad lagoon separates the beaches at Sandy Hook from the platform edge. In contrast, waves that mold the shoreline at Grotto Beach include waves that are refracted around the island in addition to waves resulting from storms/winds to the north and west. For example, the storm that pounded the northeast coast of North America in 1991 produced waves that travelled south and were several meters high on the north and west coasts of San Salvador. The effectiveness of waves to modify this shoreline at Grotto Beach is enhanced because the platform margin (drop-off) is very close to the island margin. Thus, although the prevailing wind energy suggests that higher energy beaches should be confined to the east side of the island, other factors, such as pre-existing topography (gradient, proximity to the drop-off), islands, and the growth of reefs can exert an overwhelming influence.

As we walk along the beach, patches of sand composed of mollusc shells will be seen adjacent to areas of well-sorted, highly abraded sand grains. Rounded clasts of laminated sediment are found scattered within the sand. In the upper swash area, beach bubbles can be seen.

Dig into the sand and note the planar-laminated sediments dipping seaward. Some layers are composed of fragments of mollusc shells; the sand grains of other layers are abraded, more rounded, and better sorted. Also note the rounded and cemented clasts of laminated sediment found within the beach laminations.

ERODING STRAND PLAIN

Around to the south (left as we face the ocean), there are exposed portions of an eroding strand plain. Huge boulders of laminated grainstone have calved off the eroding face of the outcrop and are partially buried in the present beach sand. If this process were arrested by cementation or continued burial, the resulting rock would likely be called an intraformational conglomerate, although clasts of laminated sediment are not necessarily "beachrock." Similar clasts are commonly found seaward of the beaches of Bimini and Joulters Cays and are interpreted to be erosion of a pre-existing early Holocene strand plain (Strasser and Davaud, 1986).

An examination of the upper surface of the outcrop suggests that it is an eolian dune surface. A hummocky topography composed of moderately well-sorted, well-rounded, laminated sediment is present there. The upper portion of the outcrop is most similar to the hummocky sands of the nearby dunes located just above the beach berm. The preservation of the lamination suggests that these dunes formed relatively rapidly—at least too rapidly for root penetration to destroy the physical laminations.

Below this eolian lithology and structures, is nearly horizontal, planar-laminated sedimentary rock which includes layers of coarser shell fragments and some intraformational clasts. These features are most similar to those seen on the adjacent beach, and they occupy the same position relative to sea level. In places, layers of flattened fenestrae, a few millimeters in length (beach bubbles?), are observed. This beach lithology contains abundant aragonite, which suggests a relatively young age. It is cemented by equant, low-Mg calcite, which suggests that it was located in a relatively high portion of the beach (see, for example, fig. 36B; remember the beach bubbles at the upper swash zone), or that it was cemented at a time when marine waters were farther removed (*i.e.*, the strand plain/beach system had been more extensive when cementation occurred).

Clasts in the paleo-beach sand include both eolian dune material and beach material. How quickly did the strand plain prograde? How quickly did it erode? Why did this sand system prograde and then erode? Would a carbonate petrologist be able to distinguish that the clasts found in the present beach at the base of the outcrop came from different subenvironments of the beach system? Would it be recognized that these features might indicate sand deposition during a slowly rising sea level?

MODERN OFFSHORE REEFS

Snorkel offshore from Grotto Beach. Small patch reefs dot the sandy bottom of this area. Some reefs are little more than rock knobs that are home to a sparse cover of corals and algae. Other patch reefs are a dense thicket of corals. The corals are growing above the level of the sand, the dominant sediment. Nowhere would this type of coral buildup be analogous to a barrier reef.

Are the rock knobs remnants of an eroded Holocene strand plain? Could the more luxuriant reefs also be located atop remnant rock knobs? What controls the distribution of these patches? What is the depth of the coral reefs? What coral species are present? What other preservable, in-place organisms are there? What would this look like in an ancient rock?

PLEISTOCENE GROTTO BEACH

Climb along the cliff just north (to the right when facing the ocean) of the beach. Note how well indurated this rock is compared to the eroded strand-plain rock. Note also the patches of *Goniolithon* and heads of coral which occur in thickets that are separated from each other by several meters. Isotopic dating of corals from this outcrop reveal that it is a late Pleistocene rock unit. What is the elevation of these corals? Does this elevation conform with our notion of late Pleistocene sea level? Can the species of corals be recognized? How does the species composition compare to the corals presently found offshore?

Exposed along the top of the cliff are planar-laminated grainstones (looks like a beach). Some laminae consist of coarser mollusc fragments; others consist of well-rounded grains (feels like a beach). In some laminae, flattened fenestrae, a few millimeters in length, are preserved (smells like a beach). Step back a little from the laminated sediment, and rotated clasts of laminated sediment of a variety of sizes are also evident. Could this really be a Pleistocene beach? How does the association of features in this grainstone compare to the present-day beach? Was the Pleistocene beach created in a similar energy regime? What is the elevation of the Pleistocene beach system? What is the vertical and lateral relationship of the laminated grainstones (Pleistocene beach) to the Pleistocene corals?

Apparently, at this location, energy conditions similar to the present existed during the Pleistocene, and a similar beach system formed about 5 m above present sea level. It is possible (and the presence of clasts suggest that it is likely) that a strand plain prograded and then eroded as the rate of sea-level rise slowed during the late Pleistocene. Accompanying the erosion of the strand plain, patch reefs formed a meter or two below sea level and within a few meters of the eroding beach/strand-plain system.

JOULTERS CAYS

Joulters Cays are the three major islands associated with the ooid sand shoal located about 10 km north of Andros Island (fig. 3, 4). The distribution of mobile sand (ebb-tidal deltas, beaches, and intertidal sand shoals) is clearly seen in the high-altitude air photo of figure 4. The channel to the south of South Joulters is relatively large and stable, whereas the channels separating the three major islands are either blocked or nearly choked with sediment. Ooid sand is transported from the south to the northern portion of Joulters, where a large intertidal sand shoal is forming. The area commonly called Joulters ooid shoal is roughly 20 km square (400 square km) and is composed of a variety of subenvironments including strand-plain islands, intertidal sand shoals, sand tidal flats, ebb- and flood-tidal deltas, mangrove marshes, shallow seagrass-stabilized sand flats, reefs, and channels in addition to more typical subtidal lagoonal environments. The sites we will visit are located on the northern portion of North Joulters Cay where many of these subenvironments can be seen. (The reef subenvironment requires a bit of a swim, and therefore will not be visited). Descriptions of the subenvironments included on the field trip are placed together at the back of this section.

Geologic research on Joulters Cays and the immediate vicinity was included in the many excellent surveys of the Bahamas in the 1950's and 1960's and was the focus of the dissertation research by Harris (Harris, 1977; 1979; Halley and others, 1983). Since then, a few studies have added to the information on the growth of the islands (Halley and Harris, 1979; Strasser and Davaud, 1986), tidal channels (Boardman and Carney, 1991) and petrology of the ooids (Carney and Boardman, 1992). The information compiled for this guidebook is largely taken from these references, personal observations, and communications with others, and is supplemented by information from research on other ooid sand shoals (Ball, 1967; Loreau and Purser, 1973; Hine, 1977; Dravis, 1979; Palmer, 1979).

A PAUSE FOR THE CURIOUS

There are many questions related to ooid sand shoals in general and Joulters Cays in particular that remain to be investigated.

<u>Where and how do marine ooids originate?</u> Ooids are magical grains. Explanations on the origin of modern marine ooids at Joulters Cays must include:

1) why they have laminae,
2) why the laminae are composed of needles of nearly the same size,
3) why the needles are in a statistically tangential orientation,
4) why the needles are monomineralic (aragonite),
5) what controls the size of ooids,
6) why there are different types of ooids (number of laminae, thickness of laminae, degree of boring, etc.)

Ideas concerning ooid origin are listed and briefly described in table 1. We have classified these ideas into three major groups. There is no clear consensus on how ooids form; although there has been a continuing effort to relate petrographic characteristics of ooids to a particular environment of formation or deposition or to a particular process of formation (Bathurst, 1975, Strasser, 1986). Further information on ooid genesis and accumulation can be found in reviews of the subject (Bathurst, 1968, 1975; Shearman and others, 1970; Fabricus and Klingele, 1970; Sandberg, 1975; Fabricus, 1977; Davies and others, 1978; Simone, 1981; Peryt, 1983).

<u>What controls the size of ooids?</u> Some areas have smaller ooids than others. The difference in ooid size is due to the number of laminae and/or to the size of the nucleus. Are small ooids "baby" ooids? The upper limit of ooid size is

TABLE 1. —*ORIGIN OF OOIDS*

IDEA	MECHANISM	PROBLEMS
MECHANICAL "Snowball" Sorby (1879)	Sedimentary needles accumulate onto nuclei either by rolling (as a snowball) or while suspended in the water column. Laminae represent episodes of agglomeration.	Why is the cortex of only one mineral; whereas the needle muds contain two major minerals (aragonite and high-Mg calcite)? What makes the needles stick?
INORGANIC Loreau and Purser (1973)	1. Grains at rest act as nuclei for precipitation of needles. Needles grow perpendicular to the nuclei, but movement of the grains bends the needles over. 2. Precipitation around grains occurs while grains are suspended in the water. Concentric laminae represent several episodes of interrupted cementation. After forming, the needles are bent over as the grains roll around.	How can precipitation occur so quickly? Why are the laminae so uniform in size—can the duration of cementation be that constant? Why do laminae completely surround the grains? How can so many perpendicular grains be created at one time (by cementation), and why aren't needles broken instead of bent?
BIOGENIC Mitterer (1968, 1972) Suess and Futterer (1972)	1. Organic matter coats grains and aids the stickiness of the surface to promote agglomeration. 2. Decay of organic matter may accelerate precipitation. 3. Bacterial activity, such as denitrifying bacteria, aids precipitation of carbonate. Dark laminae result from organic accumulation	Why a monomineralic cortex? What makes the process start and stop to produce laminae? If organic matter is everywhere, why does ooid formation occur in such localized areas? Why are the needles tangentially arranged?

presumably related to the energy of the system. Ooids continue to grow until they are too large to be moved; then they are cemented together. Alternatively, large ooids are abraded or broken if they get too big, but broken ooids are rarely seen. Shouldn't smaller ooids be winnowed from the high-energy sites of accumulation and accumulate in low-energy areas? Where are these low-energy areas with smaller ooids? In the few studies with which we are familiar, all the ooids within one general area (*e.g.*, intertidal sand shoal) have roughly the same number of laminae. Why? If ooids grow by addition of laminae, shouldn't we see ooids with only one laminae? Where are they?

Why are ooid accumulations so pure? Is there something about the ooid shoal environment that limits production of biogenic fragments (energy, sand movement)? Perkins (1986) suggested that ooids are a "default" sediment, meaning that they only accumulate where other sediment types cannot. Can this idea be verified by looking at the Joulters ooids? Perhaps the high tidal energy prevents a normal lagoonal assemblage of organisms from forming. But just to the south and the north of the Joulters ooid sand shoal are dense *Thalassia* beds, nearly intertidal, which are prolific skeletal sand producers. The energy is certainly high in these areas. To the north, large "blowout" features (Wanless, 1981) are evident in the *Thalassia* beds. Perkins' idea is important because it focuses attention on the relation of skeletal and ooid sand, but a test for it is difficult. If ooid production is higher than skeletal production, why is the area of ooid accumulation so small? What is it about the particular area of Joulters that makes it so special for producing ooids?

What controls the growth and destruction of ooid sand islands? The islands of Joulters Cays are presently being eroded, and there are no unlithified islands. Apparently there was a time of island formation and lithification. What were the special conditions that prevailed when these islands were formed?

What controls the distribution of channels? Which come first, the channels or the islands they bisect? Are channels growing longer, wider, deeper? Are they filling in? Do they migrate, or are they fixed in space? Why do many tributaries intersect the main trunks at right angles?

SUBENVIRONMENTS OF JOULTERS OOID SHOAL

Ooid distribution

It is always difficult to distinguish specific subenvironments, and the subenvironments of Joulters are no exception. Based on sand composition, there are only two major subenvironments: one dominated by ooids and one dominated by skeletal fragments and peloids. The subenvironment dominated by skeletal fragments and peloids surrounds the environments dominated by ooids. To the east (windward) the transition from ooid dominance to non-ooid dominance occurs over less than 1 km. To the south, the transition occurs over several kilometers and to the west (leeward) the ooid-skeletal transition is smeared over several tens of kilometers. We have no information on the transition to the north, but it is presumed that the transition is abrupt, although not as abrupt as that of the eastern margin.

The ooid-dominated environment can be further subdivided based on water depth and energy. Channels are areas of high ooid concentration in deeper water (>1 m deep) and contain high-energy bedforms resulting from currents (sand waves). The intertidal sand shoal, beaches, and tidal deltas are intertidal or very shallow (<1 m deep) and subject to significantly greater wave energy than the tidal channels. These three areas are part of the "mobile sand fringe" (Harris, 1979). Islands are ooid rich, supratidal, and contain multidirectional cross-bedding of small eolian dunes. The islands of Joulters consist of a series of prograded beach ridges which are now eroding along the windward margin. These environments, which are likely to become ooid grainstones, are located in a narrow band (1-2 km wide) that continues for 25 km parallel to the bank margin and then wraps around to the west for another 15 km.

Ooid packstone environments

In the more protected areas, mud and skeletal grains accumulate with the ooids. Sandy tidal flats are located directly behind the islands, and the stabilized sand flat, which forms the largest portion of the ooid shoal, is located bankward of the mobile sand fringe. These areas are shallow subtidal (<2 m) to intertidal in depth.

The distribution of ooids at Joulters can be explained in terms of energy direction and resultant redistribution of ooids. In other words, the distribution is compatible with the idea that ooids are created in a small area of the platform and are transported northward along the axis of the mobile fringe by longshore transport and bankward and offshore by storms and tides (fig. 45).

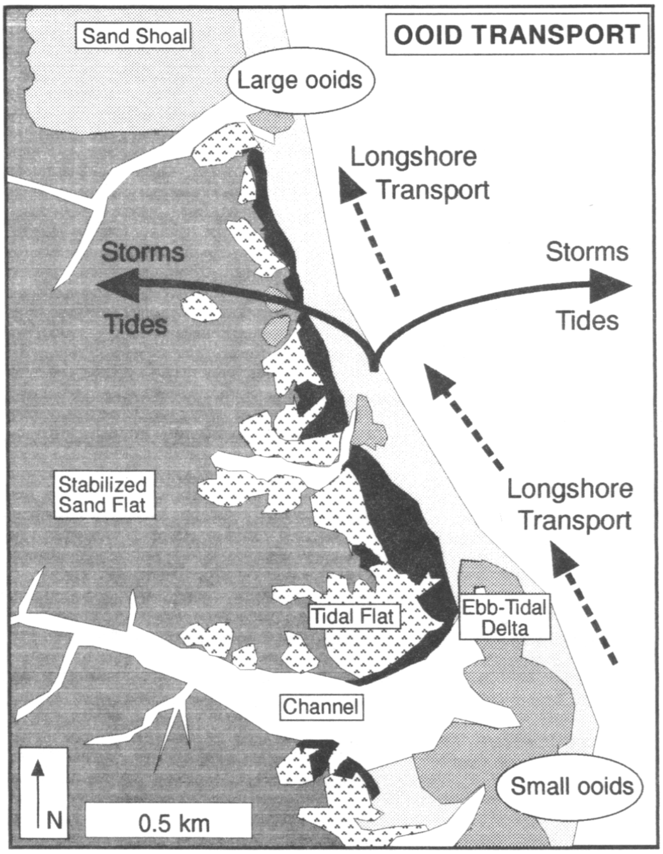


FIGURE 45.—Movement of ooids sands from the south to the north by longshore transport driven by waves. Ooids are removed from this mobile fringe by storms and tides (modified from Carney and Boardman, 1991b).

ORIGIN OF JOULTERS OOID SHOAL

The area of Joulters Cays and its history of deposition have been described in substantial detail by (Harris, 1977, 1979, 1983; Halley and Harris, 1979; Halley and others, 1983), and the following is a synopsis of this research.

Joulters developed during the Holocene flooding of the platform. The earliest sediment is a peloidal sandy mud which accumulated behind a pre-existing Pleistocene ridge approximately 5,000 years ago when sea level was approximately 5 m below present (fig. 46A). As sea level continued to rise, the platform became a shallow lagoon, and the earlier sediment was overlain by a fine peloid muddy sand (fig. 46B). When sea level was about 2 m below present (~2500 years ago), ooid sands accumulated on a topographically elevated Pleistocene area at the high-energy margin of the bank (fig. 46C). Ooid sand accumulation spread over the fine peloid muddy sand forming a broad ooid shoal with deeper channels (fig. 46D). The oolitic core of Joulters expanded northward by longshore transport. Islands formed about 1,000 years ago and prograded seaward (fig. 46E). After the islands formed, reef growth seaward of the islands accelerated (began?), perhaps in response to decreased off-bank transport of turbid, warm, and/or salty water from the lagoon. Also, the area west of the islands became better protected, and the ooid sands were mixed with skeletal and peloidal sands and minor amounts of carbonate mud (fig. 46E).

Today the seaward portions of the beach ridges are being eroded, the flood-tidal deltas are being stabilized by mangroves and seagrass, and the inlets are being choked off and reopened accompanying the continuation of longshore transport (Boardman and Carney, 1991). The major intertidal ooid sand shoal is at the northern end (see fig. 4). Here, North Joulters Cay is accreting to the north, and small hummocks and higher beach berms illustrate the continuing process of beach-ridge formation, spit accretion, and channel migration.

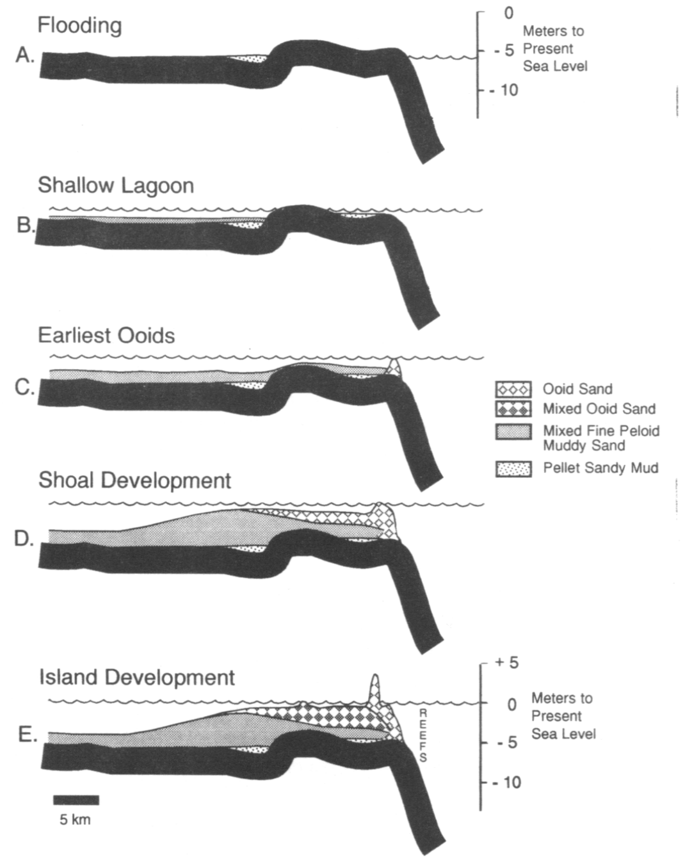


FIGURE 46.—The depositional history of Joulters ooid sand shoal (modified from Harris, 1979). **A**, as the platform is flooded, pellet sands and mud accumulate in low-lying areas. **B**, ooids are forming nearby and mix with the pellet sand and mud. **C**, a purely ooid sand shoal develops on the seaward margin and keeps up with sea-level rise. **D**, soon thereafter, ooid sands extend over the entire area of Joulters Cays. **E**, islands are formed by wave action, and a stabilized sand flat develops leeward of them and contains a mixed ooid-skeletal-peloid sand. Reefs begin to grow seaward of the islands.

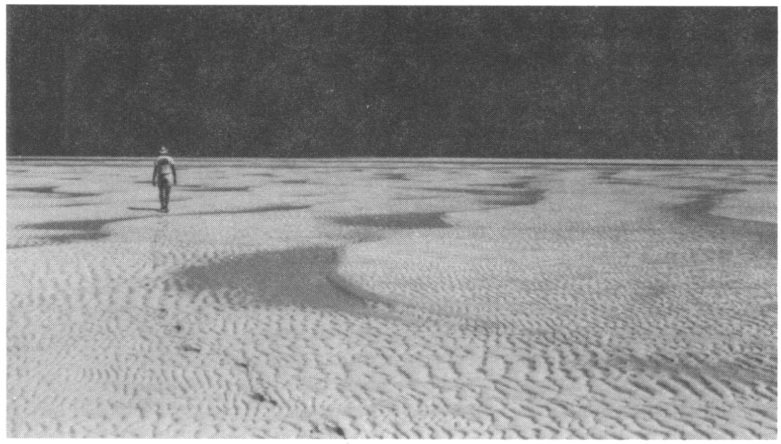
STOPS

The following pages contain information and questions about eight subenvironments (stops) located in the northern Joulters Cays area. The order and accessibility of these stops will depend on the weather, tides, waves, and the time remaining to us.

SAND SHOAL

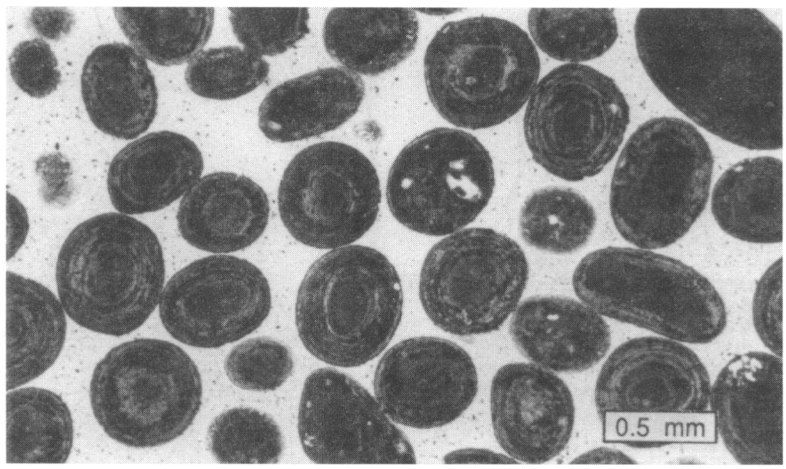
Geomorphology

The sand shoal is an intertidal sand body spreading over several square kilometers. Its surface is characterized by a variety of low-relief bedforms produced by tidal flow as well as wind-driven sheet flow. On the seaward margin, the slope is similar to that of the beach. On the bankward margin, spillover lobes with high-angle slopes are present. Small tufts of algae are commonly seen attached to cemented burrows and crusts or fragments of burrows. Algal mats of ooids are found in more stabilized areas of the shoal.



Composition

The ooids are the best developed of anywhere on Joulters Cays. Ooids average over 94% of the total grains, the highest of any subenvironment of Joulters. They are well sorted and average 0.45 mm diameter (0.11 to 0.8 mm). Ooids are characterized by numerous laminae (average of 11 laminae per ooid). The nuclei are mostly peloids and aggregates. The cortices are sometimes bored and partially micritized. There are very few uncoated grains.



Constituent	Percent
ooid	94.0
peloid/pellet	4.0
aggregate	1.5
skeletal grain	0.5

Processes

The dominant process on the shoal is grain movement. We have never been here at high tide nor during a storm, but it is likely that grains are swept bankward during flooding and high tide and when onshore winds generate shallow westerly currents. This movement would be assisted by the normal onshore trade winds. During ebb tide, the water might not be high enough to flow offbank over the shoal, so there should be no ebb-oriented bedforms (and we don't see any). The spillover lobes are likely formed during storm events (*e.g.*, Hine, 1977). Sedimentary structures are difficult to see even in cores because the grains are well sorted and because of minor bioturbation.

Questions

How much grain movement occurs during a single tidal cycle? How much during a storm event?
What is the origin of the peloids?
Why/how does micritization occur?
Do grains become oolitically coated here?
How long will this shoal remain as it is?
When will it become the foundation for an island?

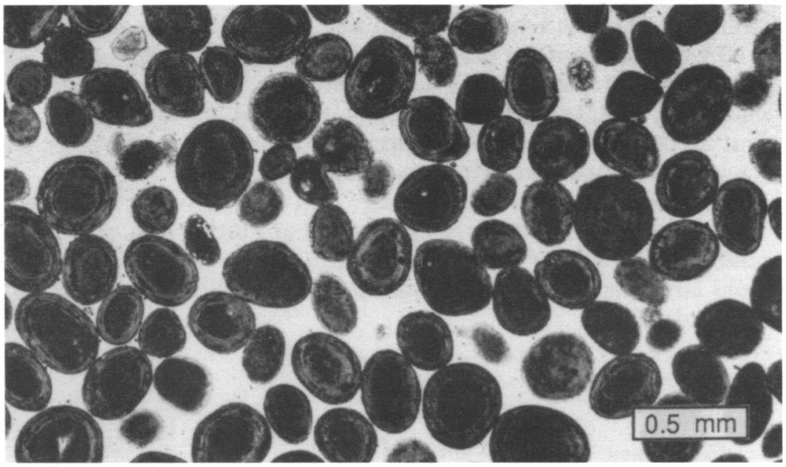
BEACH

Geomorphology

Beaches are developed on the eastern margins of the Joulters Cays. Typically, the beaches are narrow (a few meters) and abut portions of the eroding dune ridges. Offshore from the beaches are shoreface-connected ridges with relief of about 1 m. Beachrock (grains cemented by acicular aragonite) is common and dips seaward.

Composition

Beach sediments consist almost entirely of well-sorted ooids (avg. 0.35 mm; range 0.1-0.7 mm). The nuclei of ooids are composed of peloids and minor mollusc and red and green algal fragments. Ooids show slightly less boring and micritization than shoal ooids; although exterior and interior boring and rim micritization is present.



Constituent	Percent
ooid	93.0
peloid/pellet	5.5
aggregate	0.5
skeletal grains	1.0

Processes

The beach is part of the active longshore transport system. Driving the system are waves produced by the fairly constant trade winds. Parts of the dune system are eroding and adding sediment to the beach. Large dune clasts are found embedded in the beach sand. Erosion of the dune ridges indicates that sea level has risen since the ridges were created and/or that the wave climate has changed (Strasser and Davaud, 1986). Reefs are located offshore and continue to grow upward, so there should be more protection from waves.

Questions

How can the influence of an eroding dune system be recognized in the composition of the beach sands?

How can beachrock be distinguished from slumped dune rocks?

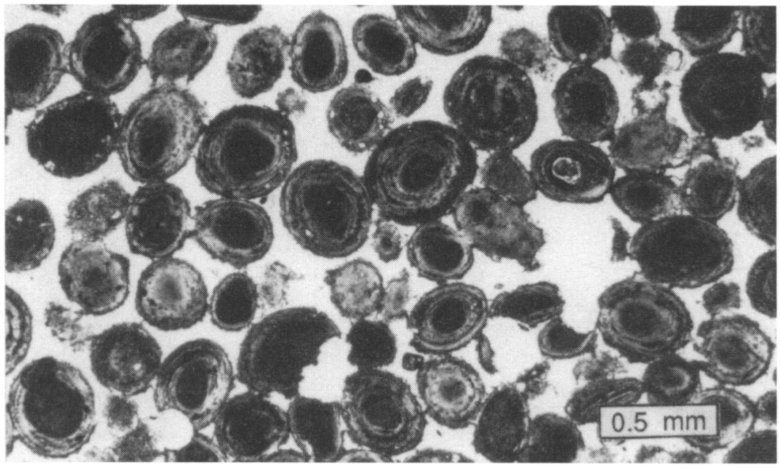
Would we ever expect a broad beach?

Why are the ooids so little micritized?

DUNE

Geomorphology

Joulters Cays consist of a series of partially cemented ooid sand ridges separated by swales. Dunes average 3 meters in height with a maximum ridge height of 5 meters (Harris, 1979). Ridges are spaced 50 meters or less apart. Bankward dunes are better cemented, more highly vegetated, and probably older than seaward dunes (Halley and Harris, 1979). A thin veneer of uncemented sand is present in the lee of dunes. Dunes are penetrated by roots of the sparse vegetation.



Composition

Dune sands consist of well-developed, well-sorted ooids which range in size from 0.1 to 0.4 mm in diameter (avg. 0.3 mm). Nuclei are predominantly peloids with some molluscs, forams, and algae. Ooids are bored but do not have extensively micritized rims. Ooids are poorly cemented, and cement is concentrated at grain boundaries. Discontinuous cement rims are present around many grains. Minor dissolution occurs along ooid laminae. The sands contain no uncoated skeletal grains.

Constituent	Percent of grains	Percent of rock
ooid	93.0	67.0
peloid	7.0	5.0
cement	0.0	11.0
porosity	0.0	17.0

Processes

Dune ridges arranged parallel to the shore are likely formed by seaward progradation. Each of the dunes was probably part of a beach-dune system. Thus, the dunes should have a composition similar to the beach except that dune sands rarely contain "large" ooids. Seaward growth of the dune system and stranding of the dune ridges requires abundant sand relative to a rising sea level. These dunes are about 1,000 years old, and are presently eroding (Halley and Harris, 1979; Strasser and Davaud, 1986). Higher trees indicate better protection from salt spray. The dunes are case hardened.

Questions

What special conditions prevailed in the past that promoted dune formation and strand-plain growth?

How much of Joulters has eroded?

Were the islands ever continuous, or were there always three? Have the islands coalesced into three?

Which island is oldest? Are they all the same age?

Why is there so little micritization of the ooid grains? How does the boring occur?

CHANNEL

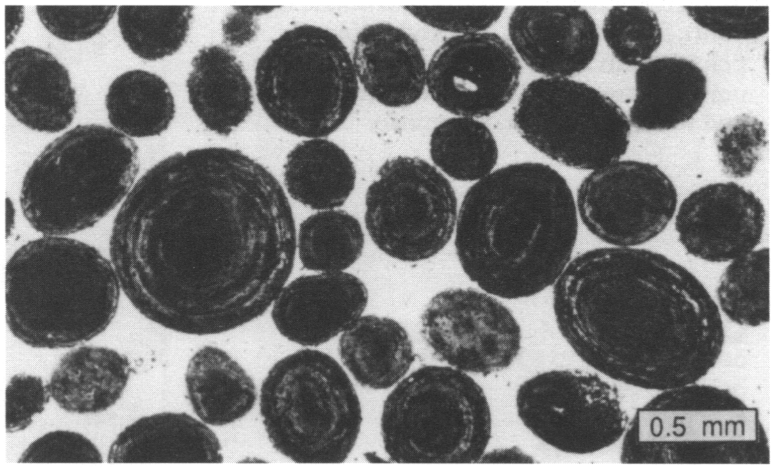
Geomorphology

The tidal channels are of various sizes and can be up to 5 meters deep and 100 meters wide (Harris, 1979). Channels are generally floored by migrating sand waves (both ebb and flood oriented) up to 2.5 meters high with wavelengths of several meters (Harris, 1979). Patches of seagrass are seen. In the troughs of some sand waves are large skeletal fragments and layers and clasts of mud. Flora and fauna are limited in the more active portion of the channels as a result of the mobile substrate.

Composition

The moderately sorted sediment is dominated by well-developed ooids which average 0.31 mm and range from 0.1 - 0.9 mm. Ooids are bimodal (0.2 mm and 0.4 mm) with nuclei predominantly composed of peloids and more rarely aggregates. Most ooids are bored, and many have micritized laminae. Uncoated skeletal grains are more abundant than in other mobile fringe environments and include forams, red and green algae, and mollusc fragments.

Constituent	Percent
ooid	82.0
peloid/pellet	8.0
aggregate	4.0
skeletal grain	6.0



Processes

High energy in the form of tidal currents is the dominant influence. The throats of channels are commonly nearly clogged with sediment moving in the longshore system (ebb-tidal delta, beach, spit, shoal). The bimodality of the sediment may result from input of smaller grains by wind or storm transport or by erosion of nearby dunes or beaches. Alternatively, ooids may be carried from the associated ebb-tidal delta where ooids have smaller diameters. Once in the channel, some of the ooids may continue to grow forming the larger ooids.

The mud is nearly pure mud (<63μm), aragonite rich (80%), and peloidal. The layers are a few to several centimeters thick, and form small chips upon excavation and erosion during migration of sand waves. The mud may be transported from the lagoon, or it may result from in situ deposition during times when the channel is closed off.

Questions

What is the origin of the bimodal ooids?

What is the origin of the mud?

How do channels form?

How do channels die?

Do channels pre-date island growth?

Do channels meander as fluvial channels do? How much? How fast?

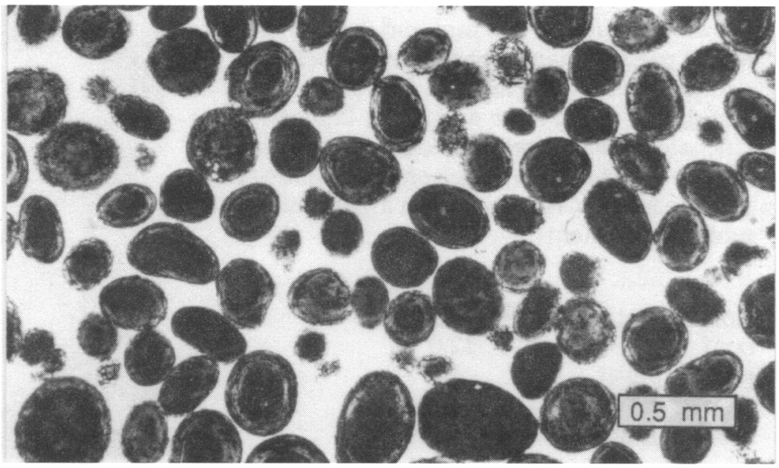
Are bedforms preserved in channels?

What is the distribution of bedforms? Are they mostly ebb or flood oriented?

EBB-TIDAL DELTA

Geomorphology

Ebb-tidal deltas form as large arcuate shallow subtidal (<1m deep) sand bodies at the mouth of each channel (sometimes making it difficult to get into the channel). At low tide, waves break on the tidal delta. Patches of seagrass occur within the tidal delta, but it is mostly undulating sand with a few deeper troughs (distributary channels).



Composition

Nearly 90% of the grains are ooids. The sediments are better sorted than the associated tidal channels. Ooid size averages 0.32 mm diameter (average number of laminae is 8 per ooid), and the nuclei are predominantly peloids with a few algae and forams. The ooids are nearly pristine; there are few borings and no micritization of laminae.

Constituent	Percent
ooid	89.0
peloid/pellet	4.0
aggregate	4.0
skeletal grain	3.0

Processes

The ebb-tidal delta is affected by high energy from waves as well as tidal currents and is a part of the longshore transport system.

Questions

Why is there so little micritization here?

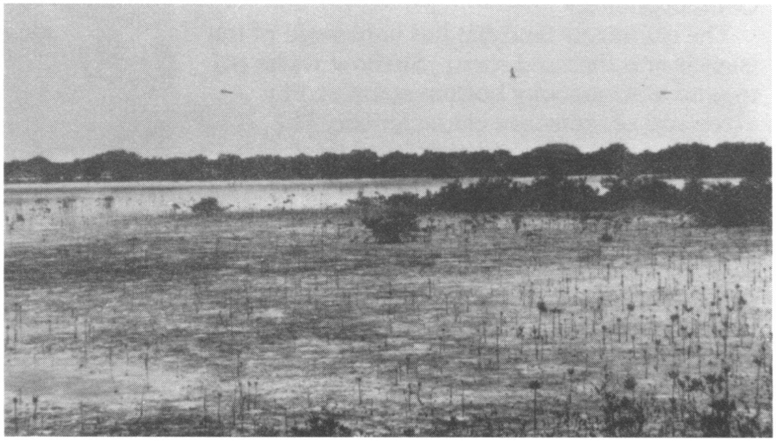
Does this mean that the grains are too mobile for micritization to occur?

Why are there so few skeletal grains?

TIDAL FLAT

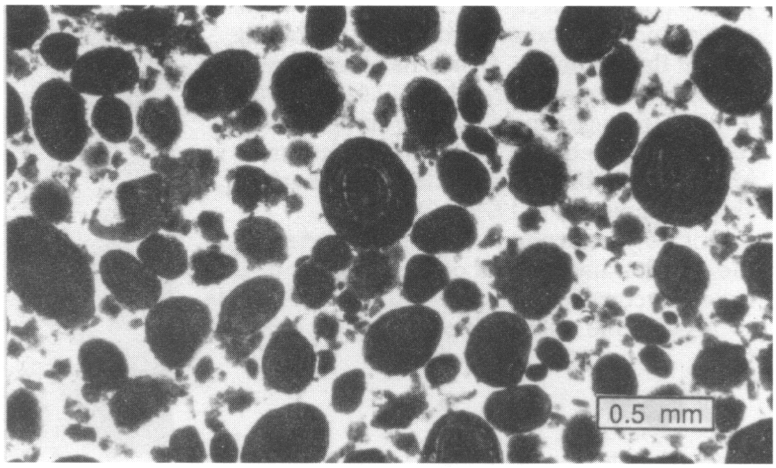
Geomorphology

Tidal flats are located behind and are protected by the island/dune system. These areas are flooded daily and are covered with a thin algal mat. Thin cemented crusts are commonly found below the surface.



Composition

Sediments consist of moderately to poorly sorted ooids, peloids/pellets, and aggregates; mud makes up less than 3% of the total sediment. Ooids average 0.26 mm in diameter (range 0.11-0.61). Most ooids are bored and partially to totally micritized. The composition of the nuclei are mostly indeterminable but probably are peloids. Uncoated skeletal grains include forams, molluscs, and green algae. Intensity of bioerosion is similar to the stabilized sand flat with numerous borings and extensive micritization.



Constituent	Percent
ooid	62.0
peloid/pellet	34.0
aggregate	3.0
skeletal grain	1.0

Processes

Large changes in salinity and temperature are expected in this environment, yet these fluctuations are still not extreme enough to eliminate the burrowing organisms that are so prevalent here. The fauna and flora are restricted to a few species. Sediment is transported from the dunes and upper beach to the tidal flats by eolian processes. It is also carried by overwash from the beach, and this dual mode of transport may be the cause of the bimodal size distribution of the ooids.

Questions

How and where does micritization of ooids occur?

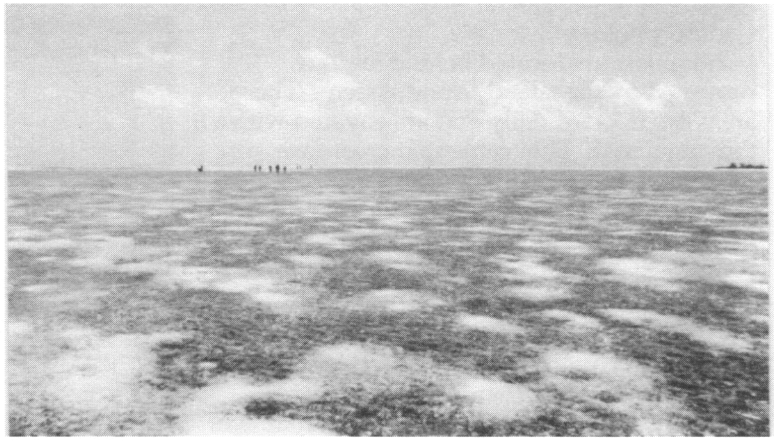
Why are there so many peloids? Are many (most) of the peloids actually micritized ooids?

What do we expect to happen during storms? Are storm layers preserved in cores?

Why is there so little mud?

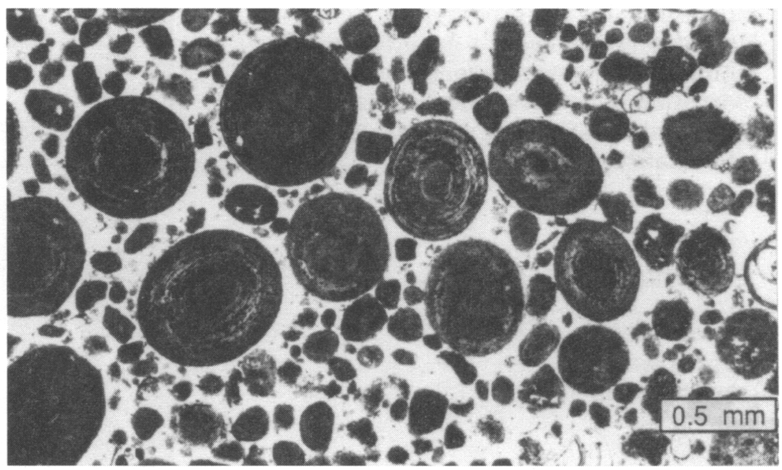
This elevation is close to that of the ooid shoal. Could some of this sediment be reworked shoal material?

STABILIZED SAND FLAT



Geomorphology

The stabilized sand flat lies bankward of the islands and the sand shoal. Shallow water (<1 m) and a hummocky bottom stabilized by algae and seagrass are characteristic. The transition with the sand shoal and tidal channels is abrupt. After walking on the beach, tidal deltas, and sand shoal, the small amount of mud present seems like a lot. The stabilized sand flat supports a variety of plant and animal life. The hummocky surface is produced by the burrowing activity of shrimp and crabs.



Composition

Sediments of the stabilized sand flat are poorly sorted and contain some mud. Ooids are the most abundant grain type, averaging 69% of the sediment. Ooids have average diameters similar to the shoal (0.41 mm; range 0.10-0.73) suggesting a source/sink relationship between these two environments or that the stabilized sand flat is a reworked shoal (Harris, 1977; 1979). Ooids are extensively bioeroded. Borings are present on the exterior and interior of the grains and rims are often completely micritized. Smaller ooids suffer extreme micritization.

Constituent	Percent
ooid	69.0
peloid/pellet	19.5
aggregate	4.0
skeletal grain	7.5

Processes

The lower energy of this environment results from protection by the islands and sand shoal. Seagrass and algal growth is relatively luxuriant, but is probably restricted by extremes of salinity and temperature. Micritization is common, and many of the peloids may be micritized ooids. The sediment is stable enough to allow micritization to proceed. Bioturbation is intense. Apparently, ooids are transported to this environment by storms.

Questions

How fast does micritization occur?

OFFSHORE

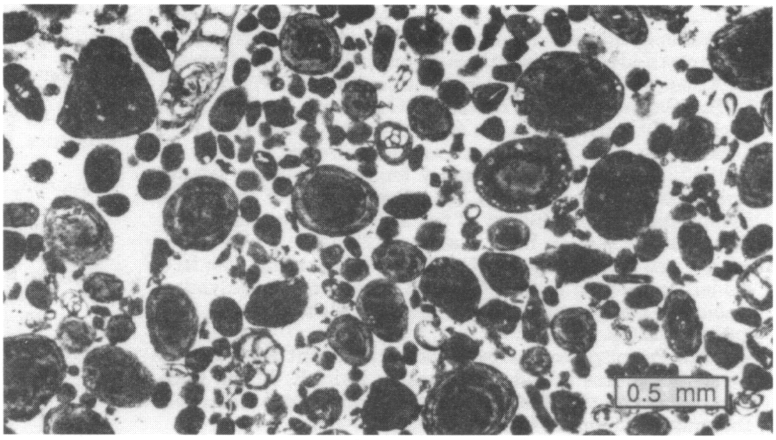
Geomorphology

Patches of sparse seagrass (*Thalassia* and *Syringodium*), sand, and some patch reefs are located offshore from the island and sand shoal. Near the islands are shoreface-connected ridges with relief of a meter and spacing of about 10 meters. Water depth gradually increases to about 5-8 meters 2 km offshore where the reefs are better developed.

Composition

The sediment is very poorly sorted and contains abundant peloids, ooids, and aggregates. Ooids average only 40% of the sediment and decrease in abundance further offshore. They are small, averaging 0.23 mm in diameter (range 0.08-0.45). Peloids and pellets make up 37% of the sediment and a relatively high percentage of skeletal grains and aggregates are characteristic. Micritization is prevalent, and it seems likely that many of the peloids are micritized ooids. Mud constitutes up to 8% of the sediment

Constituent	Percent
ooid	40.0
peloid/pellet	37.0
aggregate	10.0
skeletal grain	13.0



Processes

Apparently ooids are transported to this area by storms and ebb-tidal currents, and in this environment are micritized. The nearshore areas are perhaps more continually supplied with ooids. Because the grains are only periodically moved, aggregates form. Forams, molluscs, and algae are in situ.

Questions

Can we really believe this scenario of ooid transport and micritization? How could it be tested?

What will the C-14 age of this sediment be? What will be the difference between the age of the skeletal grains and the ooids? The ooids and the peloids?

If the ooids are transported by ebb-tidal currents, there should be a rhythmic distribution of ooids related to the tidal channels. Is this seen?

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